Opportunities for Energy Savings in the Residential and Commercial Sectors with High-Efficiency Electric Motors

Final Report

Prepared for:

U.S. Department of Energy
Contract No. DE-AC01-90CE23821

December 1, 1999

Arthur D. Little, Inc.
955 L'Enfant Plaza, SW, Suite 8600
Washington, DC
20024-2119

Reference 35495-14

Acknowledgements

The authors would like to acknowledge the valuable support provided by others in the preparation of this report. Dr. James Brodrick of D&R International provided day-to-day oversight of this assignment, helping to shape the approach, execution, and documentation. He also reviewed and critiqued multiple draft versions of the report. Mr. John D. Ryan of the U.S. Department of Energy sponsored this assignment and provided overall strategic guidance.

TABLE OF CONTENTS

LIST OF TABLES .... **III**

LIST OF FIGURES .... **V**

ACRONYMS .... **VI**

EXECUTIVE SUMMARY .... **VII**

- Introduction vii
- Study Objectives viii
- Summary of Findings viii
- Energy-Saving Technology xvii
- Market Barriers xvii
- Opportunities xviii

1 INTRODUCTION **1-1**

- 1.1 Study Objectives 1-1
- 1.2 Background 1-1
- 1.3 Work Plan and Approach 1-3

2 MOTOR TECHNOLOGY OVERVIEW **2-1**

- 2.1 Conventional Motor Technologies 2-1

2.1.1 Three-Phase Squirrel-Cage Induction Motors 2-1
2.1.2 Single-Phase Squirrel-Cage Induction Motors 2-8
2.1.2.1 Refrigerator Application of the Single-Phase SCIM 2-10
2.1.3 Shaded-Pole Induction Motors 2-12
2.1.4 Universal AC/DC Motors 2-12
2.1.5 Two-Speed Motors 2-13

- 2.2 Variable-Speed Drive and Motor Technologies 2-14

2.2.1 Efficiency Issues and Opportunities With Variable-Speed Drives 2-18
2.2.2 ECPMs 2-19
2.2.3 SCIMs With Variable-Speed Drive 2-21
2.2.4 SRMs 2-23

- 2.3 Variable-Speed Motor/Drive Costs—Refrigerator Compressor Motor Example 2-26
- 2.4 Variable-Speed Motor/Drive Costs—Fan and Small-Pump Motors 2-27
- 2.5 Current Research in Electric Motors for Commercial Applications 2-29

2.5.1 Program Options 2-31

3 MOTOR POPULATIONS, ENERGY USAGE, AND SAVINGS POTENTIAL IN THE RESIDENTIAL SECTOR **3-1**

- 3.1 Residential-Sector Motor Population and Energy Usage 3-2
- 3.2 Residential-Sector Motor Energy Savings Potential 3-11

3.2.1 Domestic Refrigerators and Freezers 3-15

3.2.1.1 Impact of NAECA Standards 3-17
3.2.1.2 Compressor Motor 3-17
3.2.1.3 Evaporator Fan Motor 3-18
3.2.1.4 Condenser Fan Motor 3-18
3.2.2 Central Air Conditioners and Heat Pumps 3-18
3.2.2.1 Single-Speed Compressor Motor 3-20
3.2.2.2 Variable-Speed Compressor Motor 3-21
3.2.2.3 Condenser Fan Motor. 3-22
3.2.3 Indoor Air Blowers in Forced Draft Heating and Air Conditioning Systems 3-22
3.2.3.1 Variable-Speed Motor/Blower 3-24
3.2.4 Room Air Conditioners 3-26
3.2.4.1 Compressor Motor 3-27
3.2.4.2 Fan/Blower Motor 3-28
3.2.4.3 Efficiency Improvement and Energy Savings Potential 3-28
3.2.5 Clothes Washers 3-29

4 MOTOR POPULATIONS, ENERGY USAGE, AND SAVINGS POTENTIAL IN THE COMMERCIAL SECTOR 4-1

- 4.1 Commercial-Sector Motor Population and Energy Usage 4-2
- 4.2 Commercial-Sector Motor Energy Savings Potential 4-5

4.2.1 Air Conditioning Compressors 4-8
4.2.2 Space Conditioning Thermal Distribution 4-10
4.2.2.1 Air Distribution 4-12
4.2.2.2 Hydronic Hot and Chilled Water Circulation/Distribution 4-15
4.2.2.3 Cooling Water Circulation 4-18
4.2.2.4 Heat Rejection to Ambient Air 4-20
4.2.3 Commercial Refrigeration 4-22
4.2.3.1 Central Systems 4-26
4.2.3.2 Beverage Merchandisers and Reach-In Equipment 4-27
4.2.3.3 Ice Machines 4-30
4.2.3.4 Refrigerated Vending Machines 4-31
4.2.3.5 Walk-In Coolers and Freezers 4-32
4.2.4 Miscellaneous Commercial-Sector Motor Applications 4-34

5 MARKET BARRIERS TO INCREASED USE OF HIGH-EFFICIENCY MOTORS 5-1

- 5.1 Residential 5-1
- 5.2 Commercial Refrigeration 5-2
- 5.3 Air Conditioning Compressors/Commercial HVAC 5-3
- 5.4 HVAC Thermal Distribution/Adjustable-Speed Drives 5-4

6 BIBLIOGRAPHY 6-1

List of Tables

TABLE 2-1: PRICE-EFFICIENCY–PAYBACK COMPARISON OF STANDARD AND HIGH-EFFICIENCY GENERAL PURPOSE THREE-PHASE MOTORS (OPEN DRIP-PROOF)....2-6
TABLE 2-2: PRICE-EFFICIENCY—PAYBACK COMPARISON OF STANDARD AND HIGH-EFFICIENCY GENERAL PURPOSE THREE-PHASE MOTORS (TEFC) 2-7
TABLE 2-3: SHADED POLE, PSC, AND ECPM REFRIGERATOR FAN MOTOR EFFICIENCY AND OEM COST....2-28
TABLE 2-4: INVOLVEMENT IN MOTOR RESEARCH FOR COMMERCIAL AND RESIDENTIAL APPLICATIONS 2-30
TABLE 3-1: MAJOR RESIDENTIAL-SECTOR ELECTRIC MOTOR APPLICATIONS—INSTALLED BASE 3-7
TABLE 3-2: MAJOR RESIDENTIAL-SECTOR ELECTRIC MOTOR APPLICATIONS—CURRENT PRODUCTION....3-8
TABLE 3-3: MISCELLANEOUS RESIDENTIAL-SECTOR ELECTRIC MOTOR APPLICATIONS....3-9
TABLE 3-4: RESIDENTIAL-SECTOR ELECTRIC MOTORS USED WITH ELECTRIC RESISTANCE HEATING DEVICES....3-10
TABLE 3-5: POTENTIAL RESIDENTIAL-SECTOR ENERGY SAVINGS THROUGH INCREASED MOTOR EFFICIENCY 3-13
TABLE 3-6: POTENTIAL RESIDENTIAL-SECTOR ENERGY SAVINGS THROUGH VARIABLE-SPEED MOTORS....3-14
TABLE 3-7: POTENTIAL FOR ENERGY SAVINGS THROUGH INCREASED EFFICIENCY AND VARIABLE-SPEED REFRIGERATOR/FREEZER MOTORS (BASE SITE MOTOR ENERGY[1]= 113 X 10^9 KWH/YR)....3-16
TABLE 3-8: COST-EFFECTIVENESS OF EFFICIENT MOTOR OPTIONS FOR REFRIGERATOR/FREEZERS—ESTIMATED PAYBACK FOR AVERAGE USER AT AN AVERAGE ELECTRICITY RATE ($0.08/KWH) 3-16
TABLE 3-9: POTENTIAL FOR ENERGY SAVINGS THROUGH INCREASED-EFFICIENCY CENTRAL AIR CONDITIONER AND HEAT PUMP MOTORS (BASE SITE MOTOR ENERGY[1] = 180 X 10^9 KWH/YR, NOT INCLUDING THE INDOOR AIR BLOWER) 3-20
TABLE 3-10: COST-EFFECTIVENESS OF EFFICIENT MOTOR OPTIONS FOR CENTRAL AIR CONDITIONERS AND HEAT PUMPS—ESTIMATED PAYBACK FOR AVERAGE USER AT AVERAGE ELECTRICITY RATE (0.08/KWH)....3-20
TABLE 3-11: POTENTIAL FOR ENERGY SAVINGS THROUGH INCREASED-EFFICIENCY INDOOR BLOWER MOTORS (BASE SITE MOTOR ENERGY[1] = 61 X 10^9 KWH/YR)....3-23
TABLE 3-12: COST-EFFECTIVENESS OF EFFICIENT MOTOR OPTIONS FOR INDOOR BLOWERS—ESTIMATED PAYBACK FOR AVERAGE USER AT AVERAGE ELECTRICITY RATE (0.08/KWH) 3-24
TABLE 3-13: POTENTIAL FOR ENERGY SAVINGS THROUGH INCREASED-EFFICIENCY ROOM AIR CONDITIONER MOTORS (BASE SITE MOTOR ENERGY[1] = 29 X 10^9 KWH/YR)....3-28
TABLE 3-14: COST-EFFECTIVENESS OF EFFICIENT MOTOR OPTIONS FOR ROOM AIR CONDITIONERS—ESTIMATED PAYBACK FOR AVERAGE USER AT AVERAGE ELECTRICITY RATE ($0.08/KWH)....3-29
TABLE 4-1: 1995 COMMERCIAL AIR CONDITIONING EQUIPMENT COMPRESSOR MOTOR CHARACTERISTICS....4-8
TABLE 4-2: POTENTIAL ENERGY SAVINGS WITH INCREMENTALLY HIGHER-EFFICIENCY COMMERCIAL AIR CONDITIONING COMPRESSOR DRIVE MOTORS....4-9
TABLE 4-3: MOTORS IN COMMERCIAL-SECTOR INTERIOR AIR DISTRIBUTION (SPACE COOLING AND SPACE HEATING—1995)....4-13
TABLE 4-4: POTENTIAL ENERGY SAVINGS WITH INCREMENTALLY HIGHER-EFFICIENCY INTERIOR AIR DISTRIBUTION BLOWER DRIVE MOTORS—COMMERCIAL BUILDINGS....4-13
TABLE 4-5: MOTORS IN COMMERCIAL-SECTOR HYDRONIC THERMAL DISTRIBUTION (1995)....4-16
TABLE 4-6: POTENTIAL ENERGY SAVINGS WITH INCREMENTALLY HIGHER-EFFICIENCY DRIVE MOTORS FOR HYDRONIC CIRCULATION PUMPS IN COMMERCIAL BUILDINGS....4-16
TABLE 4-7: COOLING WATER CIRCULATION PUMP MOTORS IN THE COMMERCIAL SECTOR (1995) 4-18

TABLE 4-8: POTENTIAL ENERGY SAVINGS WITH INCREMENTALLY HIGHER-EFFICIENCY COOLING WATER PUMP DRIVE MOTORS 4-19
TABLE 4-9: MOTORS IN COMMERCIAL-SECTOR AIR CONDITIONING HEAT REJECTION (1995) 4-20
TABLE 4-10: POTENTIAL ENERGY SAVINGS WITH INCREMENTALLY HIGHER-EFFICIENCY FAN OR BLOWER DRIVE MOTORS FOR HEAT REJECTION TO AMBIENT AIR—COMMERCIAL BUILDINGS........ 4-21
TABLE 4-11: COMMERCIAL REFRIGERATION COMPRESSOR AND FAN MOTOR ENERGY CONSUMPTION........ 4-24
TABLE 4-12: COMMERCIAL REFRIGERATION COMPRESSOR AND FAN MOTOR ENERGY SAVINGS 4-25
TABLE 4-13: ECONOMIC ANALYSIS: SUPERMARKETS 4-27
TABLE 4-14: EVAPORATOR FAN MOTOR SIZES AND OEM COSTS IN A TYPICAL SUPERMARKET 4-27
TABLE 4-15: ECONOMIC ANALYSIS: BEVERAGE MERCHANDISER........ 4-28
TABLE 4-16: ECONOMIC ANALYSIS: REACH-IN FREEZERS........ 4-29
TABLE 4-17: ECONOMIC ANALYSIS: REACH-IN REFRIGERATORS........ 4-30
TABLE 4-18: ECONOMIC ANALYSIS: ICE MACHINES 4-31
TABLE 4-19: ECONOMIC ANALYSIS: REFRIGERATED VENDING MACHINES........ 4-32
TABLE 4-20: ECONOMIC ANALYSIS: WALK-IN COOLERS........ 4-33
TABLE 4-21: ECONOMIC ANALYSIS: WALK-IN FREEZERS........ 4-33

List of Figures

FIGURE 1-1: 1995 PRIMARY ENERGY CONSUMPTION BY END-USE SECTOR 1-1
FIGURE 1-2: 1995 RESIDENTIAL AND COMMERCIAL PRIMARY ENERGY CONSUMPTION BY ON-SITE ENERGY SOURCE 1-2
FIGURE 2-1: A TYPICAL THREE-PHASE INDUCTION MOTOR 2-2
FIGURE 2-2: REPRESENTATIVE PART LOAD EFFICIENCY CURVES FOR THREE-PHASE INDUCTION MOTORS 2-4
FIGURE 2-3: NOMINAL FULL-LOAD EFFICIENCIES FOR COMMERCIALLY AVAILABLE THREE-PHASE INDUCTION MOTORS, COMPARED TO EPACT MINIMUM 2-5
FIGURE 2-4: ANNUAL OPERATING HOURS CORRESPONDING TO ONE- AND THREE-YEAR PAYBACK FOR PREMIUM EFFICIENCY GENERAL PURPOSE THREE-PHASE MOTORS 2-8
FIGURE 2-5: OEM COST OF SINGLE-SPEED INDUCTION MOTORS FOR HERMETIC REFRIGERATION COMPRESSORS VERSUS MOTOR EFFICIENCY AND COMPRESSOR CAPACITY 2-11
FIGURE 2-6: SHADED-POLE MOTOR 2-12
FIGURE 2-7: "GENERIC" VSD BLOCK DIAGRAM 2-21
FIGURE 2-8: PWM OPERATION FOR VARYING OUTPUT VOLTAGE TO A DC MOTOR 2-16
FIGURE 2-9: COMPARISON OF VARIABLE-SPEED DRIVE/MOTOR EFFICIENCIES 2-19
FIGURE 2-10: VOLTAGE AND CURRENT OUTPUT OF A PWM INVERTER 2-22
FIGURE 2-11: PWM INVERTER COSTS 2-23
FIGURE 2-12: SIMPLIFIED SCHEMATIC OF THE SRM CONFIGURATION 2-24
FIGURE 3-1: 1995 RESIDENTIAL ENERGY CONSUMPTION BY FUEL TYPE 3-1
FIGURE 3-2: 1995 RESIDENTIAL BUILDING SECTOR MOTOR INVENTORY AND MOTOR ENERGY CONSUMPTION BY HORSEPOWER RATING FOR MAJOR APPLICATIONS 3-2
FIGURE 3-3: COMPARISON OF AVERAGE EFFICIENCY OF SINGLE-PHASE TWO-POLE HERMETIC COMPRESSOR MOTORS IN THE INSTALLED BASE AND IN NEW EQUIPMENT WITH THEORETICAL LIMITS 3-3
FIGURE 3-4: COMPARISON OF THE EFFICIENCY OF OTHER SINGLE-PHASE MOTORS 3-4
FIGURE 3-5: 1995 RESIDENTIAL-SECTOR MOTOR ENERGY USAGE 3-5
FIGURE 3-6: 1995 PROPORTION OF RESIDENTIAL-SECTOR MOTOR ENERGY CONSUMPTION IN APPLICATIONS COVERED BY NAECA 3-6
FIGURE 3-7: ENERGY-SAVING POTENTIAL AND COST-EFFECTIVENESS OF INCREASED-EFFICIENCY MOTORS AND VSDS IN MAJOR RESIDENTIAL APPLICATIONS 3-12
FIGURE 3-8: VARIABLE-SPEED MOTOR/BLOWER POWER CONSUMPTION CHARACTERISTICS 3-26
FIGURE 4-1: 1995 COMMERCIAL ENERGY CONSUMPTION BY FUEL TYPE 4-1
FIGURE 4-2: 1995 COMMERCIAL-SECTOR MOTOR ENERGY USAGE 4-3
FIGURE 4-3: 1995 COMMERCIAL BUILDING SECTOR MOTOR INVENTORY AND MOTOR ENERGY CONSUMPTION BY HORSEPOWER RANGE FOR MAJOR APPLICATIONS 4-4
FIGURE 4-4: COMPARISON OF THE EFFICIENCY OF THREE-PHASE INDUCTION MOTORS 4-5
FIGURE 4-5: ALLOCATION OF COMMERCIAL MOTOR SAVINGS POTENTIAL 4-7
FIGURE 4-6: PAYBACK PERIOD FOR INCREASED-EFFICIENCY MOTORS IN COMMERCIAL APPLICATIONS 4-7
FIGURE 4-7: POTENTIAL ENERGY SAVINGS FROM MORE-EFFICIENT MOTORS AND VSDS IN COMMERCIAL THERMAL DISTRIBUTION 4-11
FIGURE 4-8: PRIMARY ENERGY USAGE IN COMMERCIAL REFRIGERATION 4-23

ACRONYMS

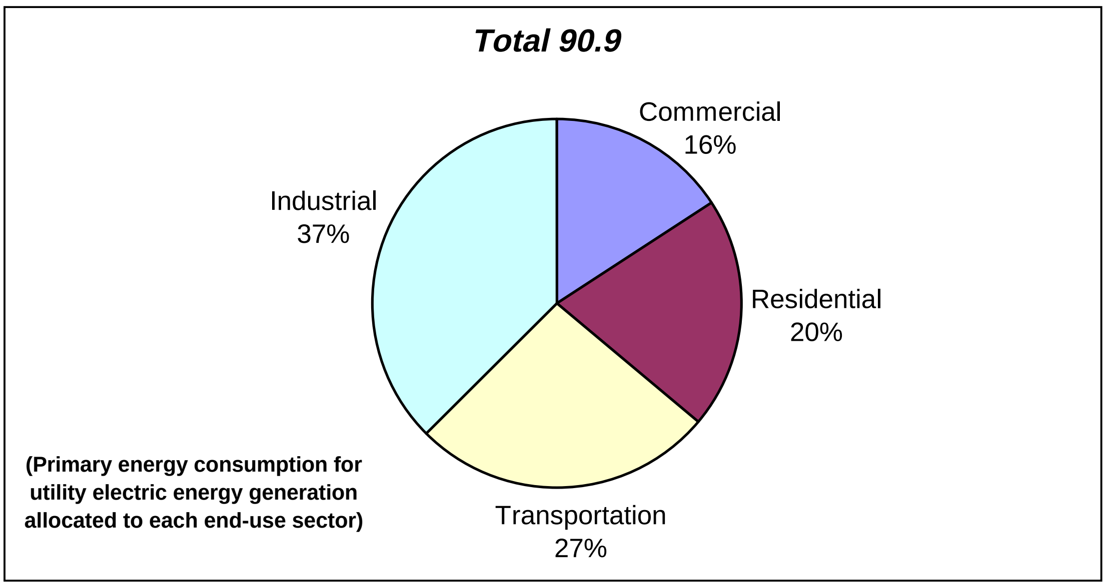
A/D	analog-to-digital
AHU	air handler units
ASD	air system design
ASIC	application-specific integrated circuit
BTS	Department of Energy’s Office of Building Technology, State and Community Programs
CAC	central air conditioner
CSCR	capacitor start/capacitor run
CSIR	capacitor start/induction run
DSM	demand-side management
DSP	digital signal processors
ECPM	electronically commutated permanent magnet
EMI	electronic magnetic imaging
ESCO	energy service company
GNP	Gross National Product
HVAC	heating, ventilating, and air conditioning
IGBT	insulated gate bipolar transistor
NEMA	National Electrical Manufacturers Association
OBE	Department of Energy’s Office of Building Equipment
OEM	original equipment manufacturer
PSC	permanent split capacitor
PTAC	packaged terminal air conditioner
PTCA	positive temperature coefficient resistor
PWM	pulse-width modulation
R/F	refrigerator/freezer
RAC	room air conditioner
RSIR	resistance start/induction run
SRM	switched reluctance motor
SCIM	squirrel-cage induction motor
TEFC	totally enclosed fan-cooled
VAV	variable air volume
VIV	variable-inlet vane
VSD	variable-speed drive

Executive Summary

Introduction

The U.S. consumed approximately 90 quadrillion Btus (quads) of primary energy in 1995. Of this energy, residential and commercial buildings consumed roughly one-third—32.8 quads. The Energy Information Administration forecasts that, if unimpeded, annual energy consumption in residential and commercial buildings will increase to 41 quads by the year 2020.

Figure ES-1: 1995 Primary Energy Consumption by End-Use Sector



Source: AEO 1998

The Department of Energy's Office of Building Technology, State and Community Programs (BTS) supports various cost-effective programs aimed at limiting the use of nonrenewable energy in buildings. To accomplish these tasks, BTS is concentrating on improving the efficiency of energy use and expanding the role of renewable energy in buildings. A specific BTS objective is to maintain energy consumption from nonrenewable sources at the current level of 32.7 quads, while accommodating and supporting the predicted growth in population, GNP, and standard of living. BTS must accomplish this objective by managing the costs of the system improvements.

In support of this objective, BTS hopes to achieve the following goals by 2015:

- The average building will use 20 percent less energy than it did in 1990.
- New homes will use 50 percent less energy than current practice.
- New commercial buildings will use 30 percent less energy than they did in 1990.

Several advanced motor technologies offer energy saving opportunities in support of these goals. This report describes these technologies and documents significant opportunities for energy savings in the residential and commercial sectors through their application.

Study Objectives

The objectives of this study are as follows:

- To develop a detailed profile of the current stock of motor-driven equipment in buildings.
- To characterize and assess the potential opportunities to reduce the energy consumption of electric motors in the residential and commercial sectors through the use of high-efficiency motors and, where appropriate, variable-speed motors.

In addition to assisting BTS in its program planning and evaluation needs, this characterization will be helpful to motor manufacturers, equipment manufacturers, distributors, and other participants in the motor industry. Residential and commercial building owners will find the study useful in guiding their own motor purchases.

Summary of Findings

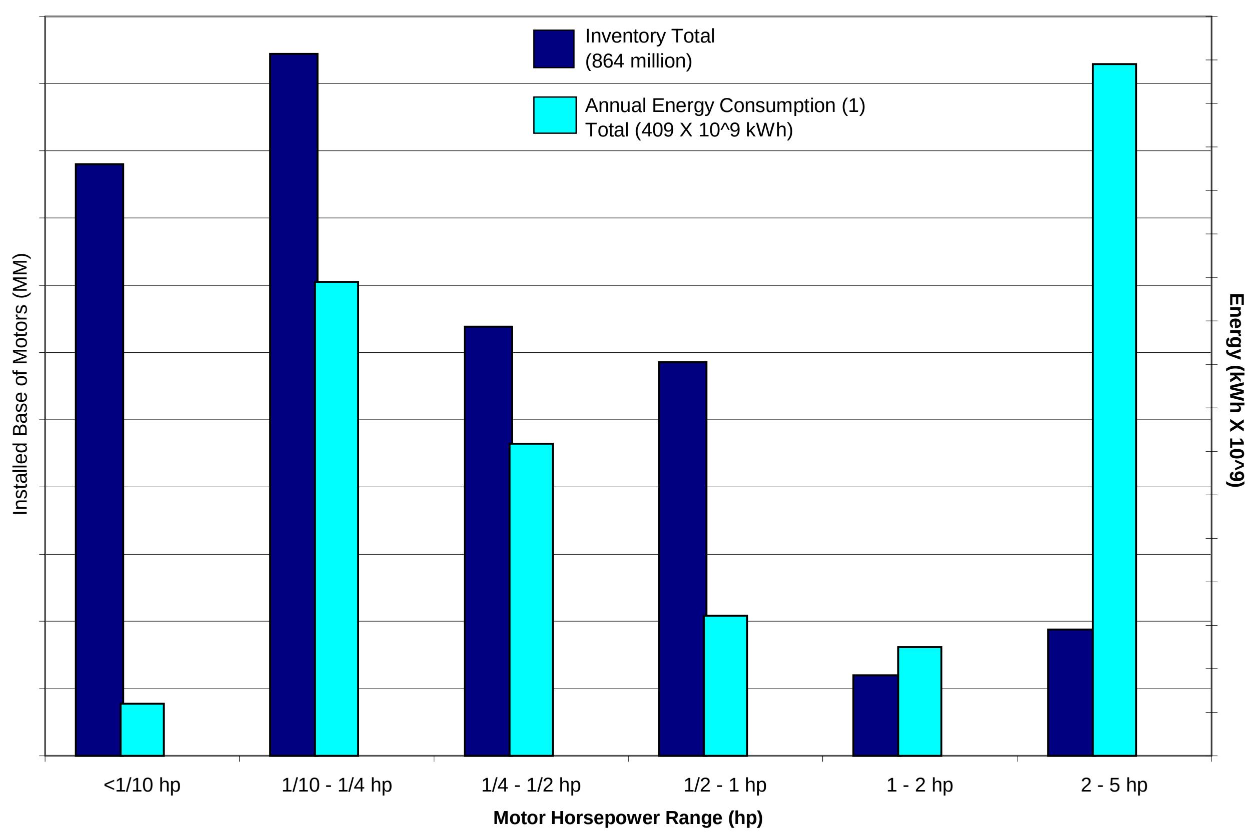
- **The total nominal output of motors installed in residential and commercial buildings is approximately 948 million hp.**

The population and energy consumption of residential electric motors in applications, other than small miscellaneous applications or motors used with electric resistance heating devices, are depicted in Figure ES-2. The total nominal output of the installed base for these motors is approximately 608 million hp, and recent annual sales of new motors for residential sector applications total approximately 56 million hp. The vast majority of the motors are installed by OEMs in comfort conditioning products, major appliances, or small appliances. In the residential sector, these motors tend to be purpose built (e.g., rotor and stators installed in refrigerant compressors) as opposed to general purpose. Even in motor sizes greater than 50 hp, OEMs purchase more than half of integral horsepower, polyphase, AC induction motors.[1]

[1] DOE/OIT, 1998

The use of motors in the residential sector is quite diverse. Motors range from the smaller motors in the 1/4 to 1/2 hp range typically used in equipment such as refrigerator/freezer compressors, central a/c condenser fans, clothes washers and dishwasher pumps to the 2 to 5 hp motors typically used in equipment such as central a/c compressors and heat pump compressors. The smallest motors in the < 1/10 hp range are typically used in equipment such as clothes dryer drum rotation and convection oven rotation motors.

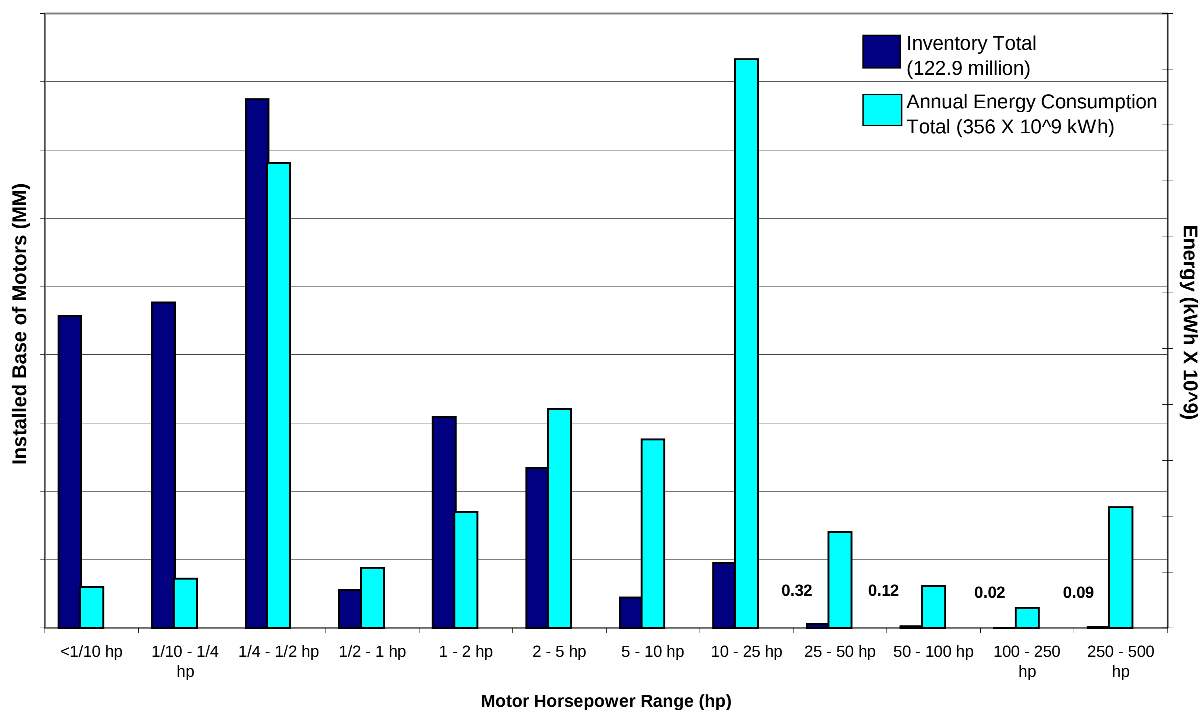
Figure ES-2: 1995 Motor Inventory and Motor Energy Consumption by Horsepower Rating for Major Applications—Residential Building Sector



Source: Table 3-1
Total does not include 34 x 10^9 kWh/year energy consumption from “Miscellaneous” sources as outlined in Table 3-3.

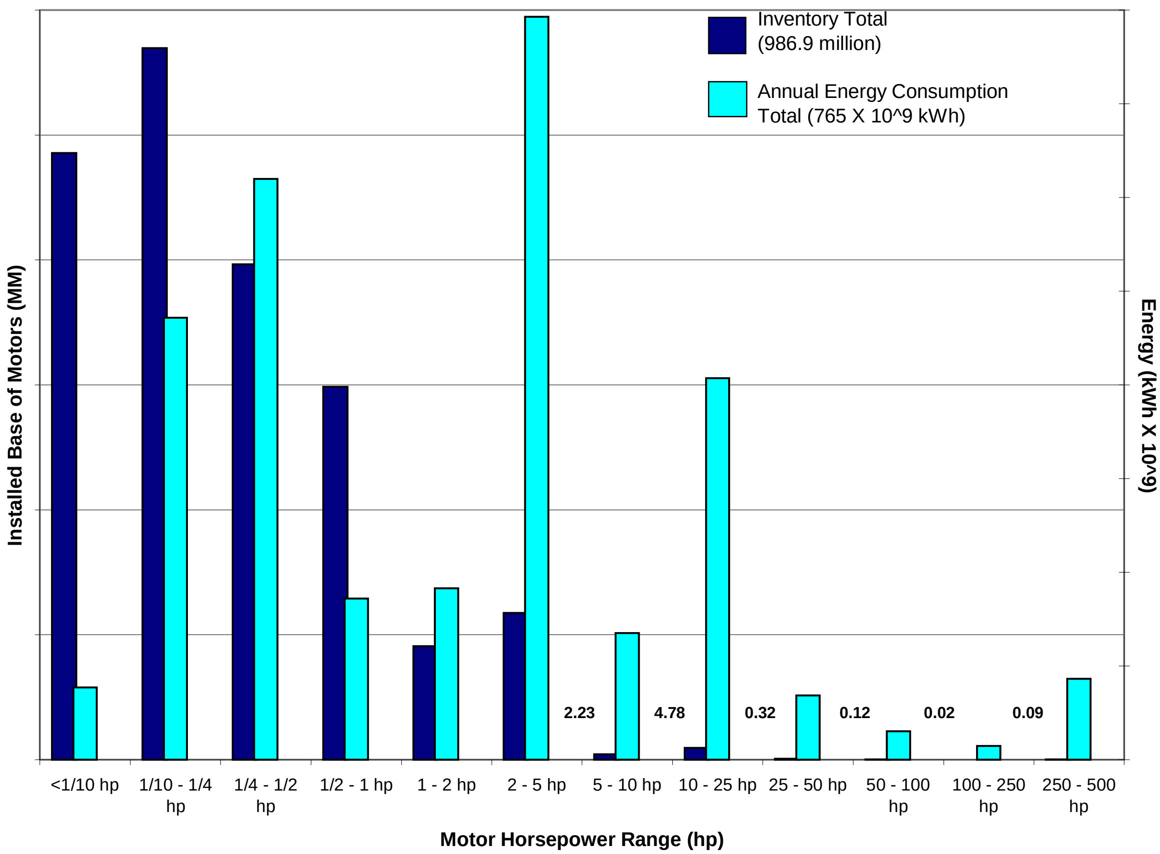
In the commercial sector (Figure ES-3), fractional horsepower motors are a small portion (approximately 9 percent) of the installed horsepower base. Uses within this category of motors, in the < 1 hp range, are typically in equipment such as room a/c fans, PTAC fans, exhaust fans, and room fan coils. Within this base, motors below 20 hp account for approximately 42 percent of the total while motors above 20 hp account for approximately 58 percent of the total installed horsepower base. Typical uses in the larger horsepower range (i.e., > 5 hp) include equipment such as unitary equipment compressors, central station air handling units, condenser water pumps, and chilled water pumps. This contrasts significantly with the industrial sector, where previous studies have estimated that 72 percent of motor energy is consumed by motors of over 50 hp capacity (only 5 percent of the motor population).

Figure ES-3: 1995 Motor Inventory and Motor Energy Consumption by Horsepower Range for Major Applications–Commercial Building Sector



Sources: Tables 4-1 to 4-21

Figure ES-4: 1995 Motor Inventory and Motor Energy Consumption by Horsepower Range for Major Applications—Total



- **Electric motors account for more than 25 percent of the primary energy consumption in the residential and commercial sectors.**

Annual electric motor energy consumption is estimated at 4.9 quads in the residential sector and 3.8 quads in the commercial sector. The figures below (ES-5 and ES-6) show the estimated breakdown of these totals by end use. These estimates were built up from equipment population, motor size, and efficiency data gathered in the course of this study.

Figure ES-5: 1995 Residential-Sector Motor Energy Usage (Primary Energy: 4.9 Quads)

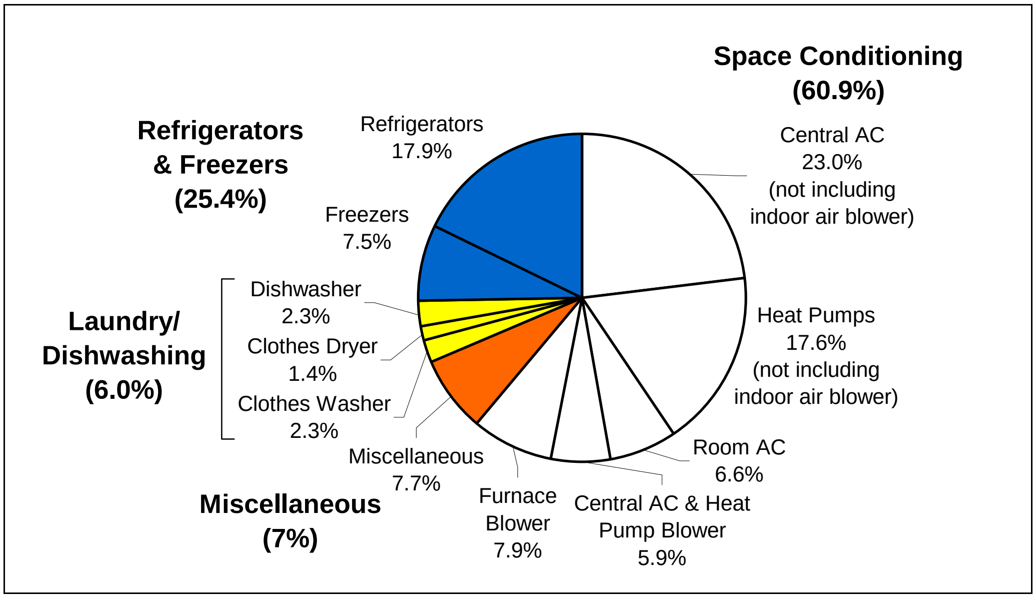
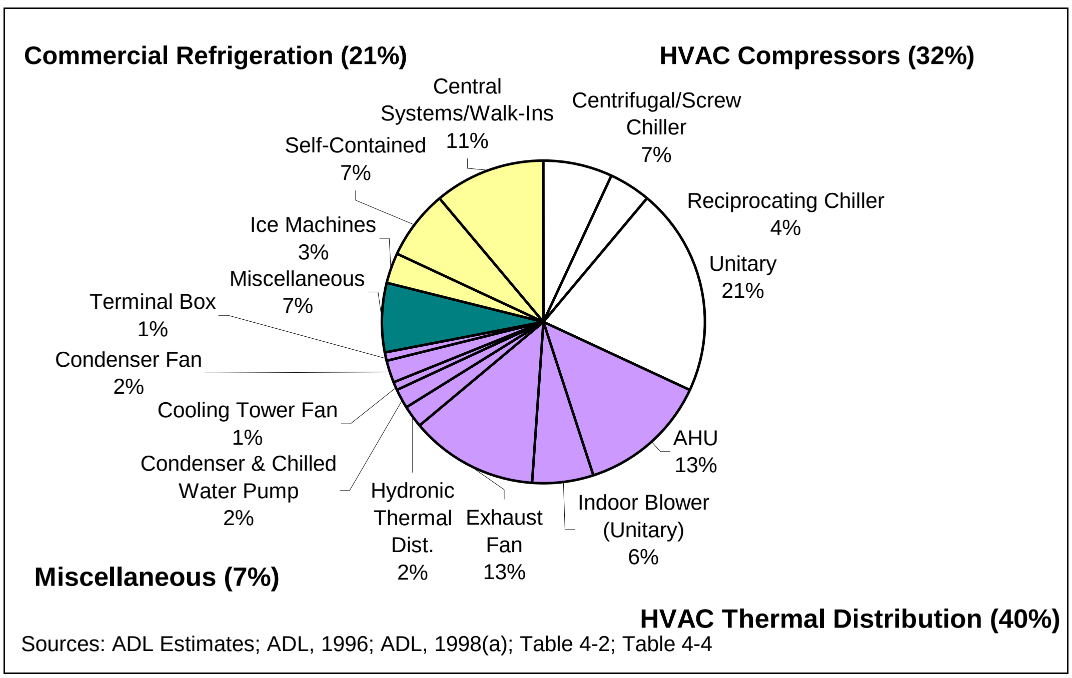


Figure ES-6: 1995 Commercial-Sector Motor Energy Usage (Primary Energy: 3.8 Quads)



Source: Figures 3-5 and 4-2.

In the residential sector, heating, ventilating, and air conditioning (HVAC) applications dominate—accounting for almost 61 percent of motor energy use. Refrigerator and freezer motor energy comprises one-quarter of the energy use. Smaller residential uses of motor energy (kitchen and laundry appliances) and so-called “miscellaneous” uses are also captured in this study.

Electric motor applications consume more than 25 percent of the commercial-sector primary energy and approximately 36 percent of the commercial-sector primary electric energy. On-site electric energy consumption of commercial-sector electric motors in 1995 was approximately 345 billion kWh; the corresponding primary energy consumption being 3.8 quads.

- **The technically-achievable annual energy savings potential is estimated at 1,604 trillion Btus in the residential sector and 564 trillion Btus in the commercial sector, totaling approximately 2.1 quads.**

In the residential sector, the technically-achievable energy savings potential is concentrated in three applications yielding 83 percent of all savings: Refrigerator/ Freezer and Freezer Compressors (14 percent), Central Air Conditioning and Heat Pump Compressors (38 percent), and indoor Air Conditioning and Heating Blowers (31 percent). Note that the “miscellaneous” motors and the motors used for electric resistance heated devices are not included in the following table.

Table ES-1: 1995 Potential Residential-Sector Energy Savings (w/VSDs and/or High-Efficiency Motors)

Application	Motor Energy 10^9 kWh/yr	Energy Savings %	Energy Savings 10^9 kWh	Primary Energy Savings “Best Options” 10^{12} Btu
R/F&F Compressor	101	20	20.2	222
Condenser Fan	6	77	4.6	51
Evaporator Fan	6	128	7.7	85
Central A/C & Heat Pump Compressor	159	35	55.7	612
Central A/C & Heat Pump O.U. Fan	21	29	6.1	66
Room A/C Compressor	25	10	2.5	28
Indoor A/C & Heating Blowers	61	75	45.9	504
Room A/C Fan/Blower	4	50	2.0	22
Clothes Washer Motor	10	13	1.3	15
Total	**393**	**N/A**	**146.0**	**1605**

In the commercial sector, the technically achievable energy savings potential is concentrated in four applications yielding approximately 88 percent of all savings: Thermal Distribution—Air Distribution (46 percent), Commercial Refrigeration—Self-Contained Unitary (20 percent), Commercial Refrigeration—Central Systems/Walk Ins (12 percent) and HVAC Compressors—Unitary (10 percent).

Table ES-2: 1995 Potential Commercial-Sector Energy Savings (w/VSDs and/or High-Efficiency Motors)

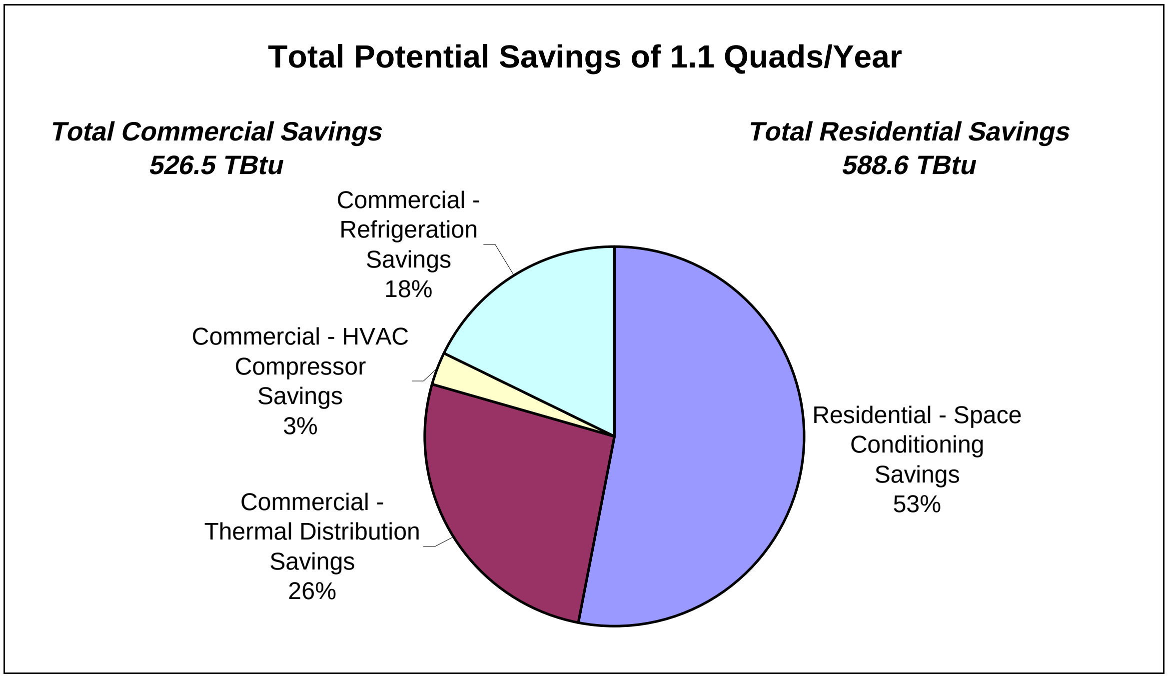
Application	Motor Energy 10^9 kWh/yr	Energy Savings		Primary Energy Savings "Best Options" 10^{12} Btu
		%	10^9 kWh	
Thermal Distribution				
Hot/Chilled Water	9.1	22	2.0	22
Cooling Water	2.4	42	1.0	11
Air Distribution	115.4	20	22.8	250.9
Heat Rejection	8.1	12	1.0	11
HVAC Compressors				
Unitary	75.2	7	5.1	55.1
Reciprocating Chillers	13.2	6	0.8	8.8
Screw/Centrif. Chillers	25.2	4	1.0	11.0
Commercial Refrigeration				
Central Systems/Walk-ins[1]	36.5	14	6.4	70.3
Self Contained Unitary[2]	23.4	36	10.2	112.2
Ice Machines	9.2	12	1.1	12.1
Total	**343**[3]	**15**	**51.4**	**564**

- **Total potential savings for measures with a five-year or shorter payback is estimated at 1.1 quads per year.**

Although this technically-achievable potential is useful as a bound on possible savings, a helpful measure of potential savings in the nearer term is the total energy savings for motor energy conservation measures having an estimated simple payback of five years or less. As shown in the figure below, when these figures are provided, the savings potentials for the two sectors appear more balanced.

[1] Includes "Small Grocery" and "Supermarket" from Table 4-12.
[2] Contains all applications under "Self-Contained" equipment type in Table 4-12 including "Vending Machines".
[3] 25.4 x 10^9 kWh/yr motor energy consumption is included from the "Miscellaneous" category of Figure 4-2.

Figure ES-7: Energy Savings for Measures With Payback of Five Years or Less (1995)



Assumptions: As documented in Sections 3 and 4, with an estimate of 85 percent of space conditioning thermal distribution savings (Section 4.2.2) through variable-speed drives being of 5 years payback or less.
Sources: Tables 3-5, 3-6, 4-2 through 4-21, Figure 4-7

- **Motor energy savings from the application of variable-speed drives, on a motor-by-motor comparison, often exceed savings from higher-efficiency motors.**

New motor technologies, powerful in their versatility, are available in large part due to the decreasing cost and growing sophistication of electronics for motor drive systems, including variable-speed drives (VSDs). Also, higher-efficiency motors are available using technology that has long been commercially available but at higher first costs. Thus, two paths exist to improve the efficiency of motor use:

- Use of higher-efficiency induction motors or higher-efficiency motors of other configurations
- Use of motors (of any configuration) using multiple speeds or variable-speed drives to achieve higher efficiency and other benefits

In the residential sector, variable-speed technology doubles the motor energy savings from 23 x 10^9 kWh/year to 46 x 10^9 kWh/year, as shown in the following table. Application of the most appropriate measure for each motor technology increases the total five-year payback savings to 54 x 10^9 kWh/year.

Table ES-3: Energy Savings From More-Efficient Motors and Variable-Speed Motors—1995 (10^9kWh/yr)

RESIDENTIAL	Efficient Motor Savings	Variable-Speed Motor Savings	Combined "Best Options" Motor Savings
Energy Consumption	389	350	389
Technical Potential	45	126	146
Five-Year Payback	23	46	54

COMMERCIAL	Efficient Motor Savings	Variable-Speed Motor Savings	Combined "Best Options" Motor Savings
Energy Consumption	343	343	343
Technical Potential	42	32	51
Five-Year Payback	40	32	48

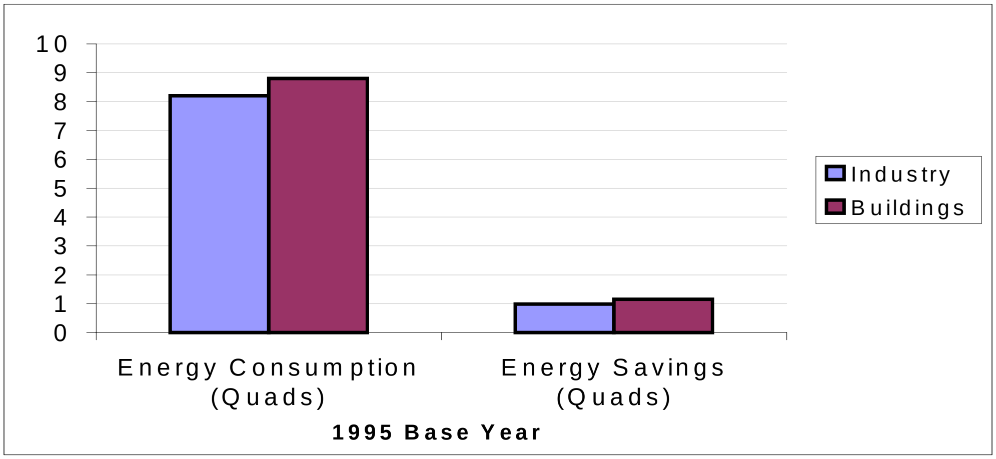
Sources: Tables 3-5, 3-6, 4-2 through 4-21, Figure 4-7

In contrast, the commercial sector has a slightly higher savings potential due to high-efficiency motors (42 x 10^9 kWh/year) versus the savings potential due to variable-speed drives (32 x 10^9 kWh/year). One possible reason for this anomaly is the fact that chiller manufacturers are not currently using VSDs on the majority of their compressor equipment. For the most part, load variability in an HVAC system is handled by loading and unloading the chiller compressor with a load-limiting system. Variable-speed drives are typically not used on the compressor. It is expected that as the cost of VSDs declines and their acceptability and dependability increase chiller manufacturers will use them more often on their equipment.

- **The magnitude of energy consumption and potential motor energy savings in residential and commercial buildings approximate those of the industrial sector.**

A recent study prepared for the Department of Energy in support of the Motor Challenge Program reported industrial motor energy consumption at 747 billion kWh or 8.2 quads primary energy. Based on a detailed analysis of the industrial motor systems inventory, the study estimates that application of all cost-effective system measures (three-year simple payback) would yield annual energy savings of 72 to 107 billion kWh (.8 to 1.18 quads). These measures include the application of VSD and other process improvements.

Figure ES-8: Comparison of Energy Consumption and Savings by Motors in the Building and Industrial Sectors



Energy Savings: For industry, motor and system savings with a three-year or less payback. For buildings, motor and VSD measures only with a payback of five years or less.

Energy-Saving Technology

From this report it is evident that significant energy-saving opportunities exist in several areas. Among the most promising:

- Variable-speed compressors/variable-speed fans for home refrigerators
- Variable-capacity compressors/variable-speed indoor blowers for residential furnace fans and small commercial air conditioning
- Efficient evaporator fans in commercial refrigeration equipment
- Variable-speed blowers in commercial space conditioning air-handling equipment
- Reduction of parasitic and other losses in commercial building thermal distribution systems—hydronic circulating pumps, cooling water pumps, and heat rejection fans, as well as conditioned air handling

Market Barriers

Achieving this savings potential will require addressing significant market barriers. The motor and variable-speed drive markets have numerous stakeholders with many different, sometimes conflicting, interests. Interested parties include building occupants, motor and drive manufacturers, OEMs, appliance manufacturers, equipment distributors, trade associations, electric utilities, certification organizations, research centers, government agencies, engineering firms and construction companies. The exact role and relative importance of each stakeholder can vary significantly across markets and even within markets. Similarly the importance and precise nature of market barriers varies by sector (residential or commercial) and motor application (appliances, HVAC equipment, refrigeration, thermal distribution systems). For instance:

- In residential appliances, the primary barrier to the use of incrementally more-expensive, higher-efficiency components is the combined effect of typical consumer appliance purchase-decision priorities and the stringently competitive pricing faced by manufacturers, distributors, and retailers.

- In residential applications, variable-speed motors have not yet proven very cost-effective.

- For commercial refrigeration applications, it is useful to distinguish between end-users that pay their own energy costs and those who do not. For example, most vending machines are owned by bottling companies who do not pay utility bills in the buildings where the units are located. By contrast, supermarkets are responsible for their own energy bills.

- One of the main issues influencing the acceptance of VSDs in the design phase of commercial building is the lack of trained and experienced consulting engineers with the knowledge necessary to design these systems.

Opportunities

There are many opportunities for energy savings in the residential and commercial sectors using high-efficiency electric motors. Many applications are already promising in terms of costs, availability, efficiency, and energy-savings benefits. However, some of the more efficient of the identified technologies are commercially available, but lack the critical production level necessary to be economically viable. Because new technologies often involve a relatively high risk-to-reward ratio for manufacturers, market forces alone may not ensure that these technologies will be available to end-users. In many areas there is a clear role for DOE. For example, DOE initiatives could include the following:

- DOE could provide assistance to private industry, universities, or non-government agencies that undertake motor research activities, to encourage the development of new motor technologies.
- Working with motor manufacturers, DOE could urge OEMs to integrate efficient motors and VSD technology in their HVAC or refrigeration products.

- BTS could establish a Motor Challenge for Buildings to stimulate information exchange between residential- and commercial-appliance manufacturers, applications designers, and commercial end-users.
- DOE could endorse training initiatives for small motors and their application, in partnership with trade associations.

These are but a few of the potential measures open to DOE and motor-efficiency stakeholders. The findings and detailed analysis in this study will be helpful to BTS in its program planning in support of motor manufacturers, equipment manufacturers, distributors, and other participants in the motor industry.

1 Introduction

1.1 Study Objectives

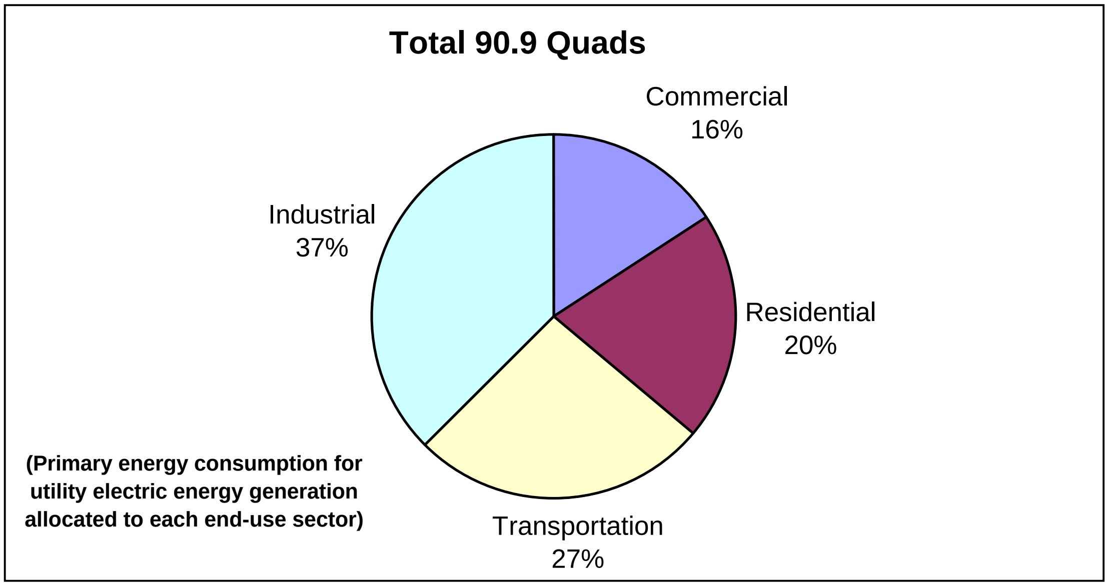
The objectives of this study are:

- To develop a detailed profile of the current stock of motor-driven equipment in buildings
- To characterize and assess the potential opportunities to reduce the energy consumption of electric motors in the residential and commercial sectors through the use of high-efficiency motors and, where appropriate, variable-speed motors

1.2 Background

As indicated in Figure 1-1, the residential and commercial sectors accounted for nearly 33 quads, or 36 percent, of the total U.S. primary energy consumption in 1995. Electric motors consume a significant fraction of electricity consumed in the residential and commercial sectors, as shown in Figure 1-2, accounting for approximately 8.7 quads (primary energy) in these two sectors. Within the past several years, several studies have examined the opportunity for saving electric motor input energy (throughout the U.S. economy, including the industrial, residential, and commercial sectors).

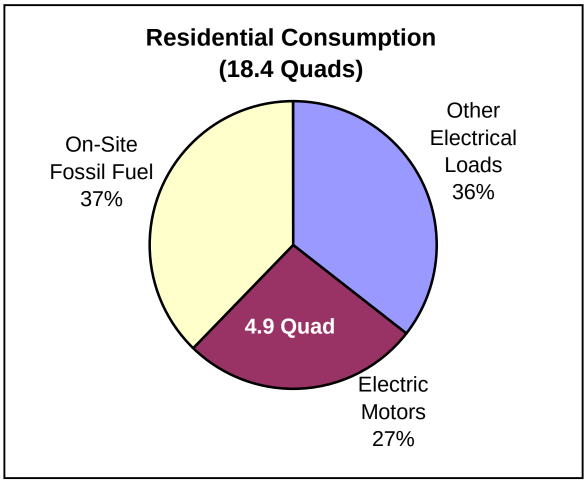
Figure 1-1: 1995 Primary Energy Consumption by End-Use Sector

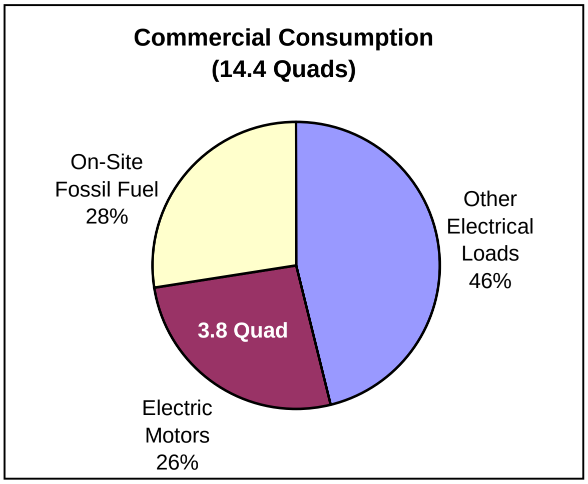


Source: AEO 1998

Figure 1-2: 1995 Residential and Commercial Primary Energy Consumption by On-Site Energy Source

(Primary energy consumption for utility electric energy generation allocated to each end use sector)





Sources: AEO 1998, Electric Motors Consumption from this Report

These studies, which have generally concluded that large energy savings could be realized, include the following:

- Electric Motors–Markets, Trends and Applications, EPRI TR-100423, June 1992.
- Energy-Efficient Motor Systems–A Handbook on Technology Programs, and Policy Opportunities, published in 1991 by the American Council for an Energy-Efficient Economy (ACEEE).
- The State of the Art: Drivepower, a Competitek Report published by the Rocky Mountain Institute, April 1989.
- Technology Assessment: Adjustable-Speed Motors and Motor Drives (Residential and Commercial Sectors), Lawrence Berkeley Laboratory, LBL-25080, March 1988.

These documents provide a useful overview of the overall motor populations and their energy usage and describe a wide range of technology options. However, they have the significant limitation that the residential and commercial sector motor installed base and current production is not broken down by the application area. Consequently, the energy saving potential based on in-use vs. potential efficiency, power level, annual operating hours, and the cost-effectiveness of efficiency upgrades cannot be accurately assessed. It is necessary to quantify the available opportunities for electric energy savings using high-efficiency electric motors and adjustable-speed drives in the residential and commercial sectors. It is also important to assess the installed base and current sales by major applications. This would help the Office of Building Equipment (OBE) decide on appropriate action. This study develops estimates of energy use and potential energy savings by motor application in the residential and commercial sectors. It also evaluates the cost-effectiveness of the potential energy savings and identifies various motor technology options. An assessment of present efficiency standards (e.g., NAECA, EPAct, and ASHRAE Std. 90.1) is conducted to determine the long-range effects on the industry. Market barriers to the use of cost-effective, high-efficiency options are also identified to help formulate programmatic options.

The prior studies have viewed the question of energy savings potential for motors from the point of view of the complete system. In addition to the efficiency characteristics of the motor, they considered the power quality of the input electricity and the efficiency of the driven device or process. This is a valid and useful way to view the energy savings opportunities. Unfortunately, this increases the scope of the problem from one of motor technology and performance characteristics to an examination of the technology of a wide range of other types of equipment. The OBE has already been systematically examining the energy savings opportunities at the system level for the major residential and commercial-sector energy consumers. *Therefore, the scope of this study is confined to the opportunities to save energy through motor efficiency improvement only*. There are two primary dimensions to this examination:

- Substitution of a higher-efficiency, but otherwise identically performing, motor for a lower-efficiency motor currently in use.

- The use of variable-speed drives for varying loads such as pumps and blowers; The variable speed can take advantage of the favorable part load speed-output-efficiency characteristics (e.g., the third power of speed law for blowers) to force air or liquids through a system of fixed flow resistances.

1.3 Work Plan and Approach

This assessment of the opportunity to improve motor efficiency has three tasks:
- Task 1: Basic Data Collection
- Task 2: Technology-Improvement Opportunities
- Task 3: Market-Penetration Barriers

The first two tasks provide an assessment of the current market situation for residential and commercial electric motors, examining sales of both conventional and high-efficiency motors and their current prices. Given the low market penetration of some high-efficiency options, the cost structure is examined to identify the opportunities for reduction of installed cost through the economies of scale associated with mass production, design modification, or technology development.

The last task describes various barriers to the increase in utilization of high-efficiency options. It examines the hurdles that are present by segmenting the market into smaller subsections. Each subsection has different reasons for not using the high-efficiency option. Some are market-driven, others are company-driven. Overall, this task identifies many difficulties to overcome if the high-efficiency options are to become prevalent within the market.

This report documents the results of the above tasks and provides an overview of the U.S. market for residential and commercial motors, covering both conventional technologies and commercially available high-efficiency options. It focuses on increasing the use of improved motor technology. It covers many high-efficiency motor technologies that are currently commercially available, including:

- High-efficiency single-phase and three-phase induction motors
- Variable-speed drives
  - Inverter-driven induction
  - Electronically commutated permanent magnet rotor DC motors

A basic description of each conventional and high-efficiency technology is provided along with current sales and cost information. The economic attractiveness of the high-efficiency options is examined for a representative range of electric utility rates; at both current price and installation cost levels, and estimated mass-production costs.

Task 1: Basic Data Collection

This task included an application-by-application ("bottom-up") assessment of motor population and energy consumption, and potential motor-energy savings (while accounting for current economic incentives).

Key issues addressed were:

- Characterization of the existing population and current sales distribution, motor types (e.g., shaded pole, permanent split capacitor), power and efficiency ranges, and duty cycle (annual operating hours) of motors used for major residential- and commercial-sector end uses.

- Characterization of the energy consumption of the existing motor population.

- Identification of the highest-efficiency motors currently available and the associated cost premium for the end user; Simple paybacks due to energy cost savings were estimated for each application.

- Identification of applications where significant seasonal energy savings could be realized using a variable-speed motor drive.

- Identification of non-commercialized technologies with potential for higher efficiency or lower cost premiums.

- Estimation of the potential national energy savings attainable for each major residential/commercial-sector application and identification of the priority applications and horsepower size range.

- Identification of applications whose motor efficiency is currently driven or will be driven in the future by energy-efficiency legislation (e.g., NAECA, EPAct).

In each application with a significant energy savings potential, the margin for efficiency improvement of the currently installed base was examined for a normal replacement cycle by upgrading the efficiency level of current production and sales levels. In some instances, the feasibility of accelerated efficiency upgrades through early retrofit was also examined.

Task 2: Technology-Improvement Opportunities

The emphasis of this task was on technologies that are in the development or early commercial stages. Opportunities were evaluated to improve motor technology by considering the potential for efficiency improvement and/or cost reduction. Potentially important technology areas include developmental motor technologies (e.g., switched reluctance), early commercial technologies (e.g., permanent magnet rotor, electronically commuted DC motors) and adjustable-speed drive electronics technologies, that can reduce cost or improve the overall performance (e.g., vector control). For each technology, the applicable speed and power range was identified and development needs were identified. For each major motor application, the overall energy savings potential of the best current technologies and new technologies were calculated and summarized.

Task 3: Market-Penetration Barriers

This task identified the barriers to the use of high-efficiency motors and/or motor drive systems for applications. These barriers can be purely economic, institutional, or technological. An example of an economic barrier is an inadequate return or a payback that is too long on the additional cost of the high-efficiency motors. With the business concentration being on increasing the firm value to the stockholders, any research or equipment purchases must have a quick and attractive turnaround on the money invested. An institutional or corporate barrier exists when there are split responsibilities within an organization for equipment purchase and energy costs. This leads to a concentration on the first cost of the equipment rather than the first cost and operation of the equipment. The high-efficiency motors are overlooked in favor of low-cost alternatives. The final barrier identified is purely technical. There is a need for sensor and control technology to take advantage of VSDS within applications. As the development of newer and more accurate digital and computer controls commences for the motor application field, they will create expanded opportunities for VSD use.

2 Motor Technology Overview

This section provides a brief description of the motor technologies commonly used in the residential or commercial sectors and of advanced motor technologies that might be applied to gain efficiency in either sector. While the treatment of each technology may not be comprehensive, the basic principles of operation and efficiency characteristics are reviewed at length.

2.1 Conventional Motor Technologies

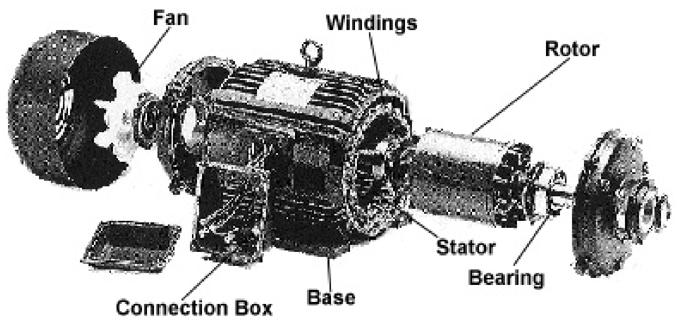
Single-speed induction motors are currently in use in most of the motor applications in the residential and commercial sectors and constitute a sizeable majority of the motor population. Induction motors are a popular choice for many other miscellaneous applications as well (with total motor-energy consumption a small part of the sector totals). Some examples include the use of a brush-type universal AC/DC motor in vacuum cleaners, some power hand tools, and other applications requiring a low duty cycle.

An electric motor converts electrical energy into mechanical energy. Consequently, the selection of a motor for a particular application should involve analysis of many factors relevant to the particular process. Issues such as starting torque and acceleration, speed, load, duty cycle, service conditions, and power factor may override consideration of a simple efficiency versus initial cost analysis.

2.1.1 Three-Phase Squirrel-Cage Induction Motors

Three-phase squirrel-cage induction motors (SCIMs) are used as the prime mover for the majority of commercial- (and industrial-) sector motor applications requiring over a few horsepower, and in many smaller motors, as well. They are readily available in two-, four-, or six-pole configurations (corresponding to speeds of 3,500; 1,750; or 1,150 rpm; respectively). Configurations with more pole pairs and slower speeds are also available. Figure 2-1 illustrates an integral horsepower, three-phase, SCIM in a totally enclosed fan-cooled (TEFC) housing. As may be seen in this illustration, air is directed over the ribbed exterior of the housing body by a shrouded external cooling fan.

Figure 2-1: A Typical Three-Phase Induction Motor



Picture courtesy of LEESON Electric Corporation.

The typical three-phase induction motor employs a wound stator and a “squirrel-cage” rotor, depicted in Figure 2-1. Magnetic force acting between the stator and rotor units produces motor torque. The stator consists of a hollow cylindrical core formed by a stack of thin steel laminations. Insulated copper windings are assembled into slots formed about the inner circumference of the core. Typical stator coil turns carry current through one slot and then back though a companion slot located approximately one pole pitch distant from the first. For a two-pole motor, the pole pitch is half the circle, while for four- or six-pole machines it is one quarter or one sixth of the circle, respectively. The portion of the turn bridging one slot to the next is part of the winding “end turn” bundle formed at each end of the stator core.

The rotor unit consists of a laminated steel core press fitted to the steel shaft. Like the stator, the rotor core also has windings set into slots but these are deployed about its outer circumference. Moreover, in the “squirrel-cage” rotor configuration the rotor windings consist of solid conductor bars that are interconnected at either end with solid-conductor end rings. Absent the laminated steel core this assembly of bars and end rings would look like a squirrel cage, and hence the nomenclature for this very robust and cost-effective construction. As the voltage between the conductor bars and the rotor core drops, a non-conductive oxide film is formed between the rotor bars and the rotor core slots providing sufficient insulation.

When the stator windings are energized by a three-phase electrical source, a radially directed magnetic flux is established in the “air gap” between the outside diameter of the rotor and the inside diameter of the stator. This flux rotates at a speed determined by the electrical frequency and number of poles given by the stator-winding configuration. For example with
60 Hz excitation and a 2 pole (or 1 pole-pair) winding the flux rotates at a so-called “synchronous” speed of 60 revolutions per second (rps) or 3,600 revolutions per minute (rpm). The flux produced by the energized stator windings envelops the rotor cage bars

and due to its motion induces current to flow in these conductors. The interaction of the rotating stator flux and the rotor bar currents develops motor drive torque.

Important characteristics of the three-phase SCIM are simplicity and ruggedness, inherently high starting torque (without the start-assisting devices required for single-phase motors), and the potential to achieve high-efficiency. The torque-speed-efficiency curves shown in Figure 2-2 depict important aspects of induction motor performance for several power levels. Salient performance characteristics associated with these curves are as follows:

- At synchronous speed (3,600 rpm/pole-pairs) the torque output is zero. As the driven device applies increasing load (torque), the motor speed falls gradually. Slip is the difference between synchronous speed and actual operating speed, typically expressed as a percentage of the synchronous speed.

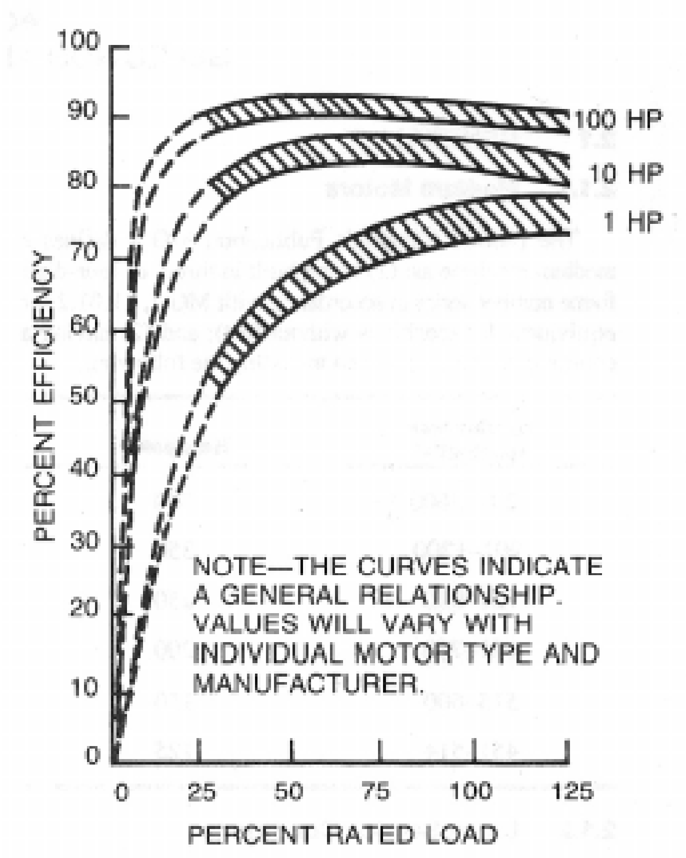
- Rated power output generally occurs at 1 to 3 percent slip within limits based on the continuous power and heat dissipation level consistent with the motor design temperature rise limit.

- The maximum torque output, referred to as the breakdown torque, usually occurs between 10 and 20 percent values of the slip. At this torque level, the motor is highly overloaded and cannot sustain operation beyond a few minutes (or less).

- The efficiency peak of larger (e.g., > 1 hp) three-phase induction motors is fairly broad, so that over a range of 40 to 125 percent of the full load, the motor efficiency is within a few percentage points of its peak efficiency.

- Generally, the full load efficiency of motors increases as the motor horsepower rating increases.

Figure 2-2: Representative Part Load Efficiency Curves for Three-Phase Induction Motors



Reprinted from "Energy Management Guide For Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors", NEMA Standards Publication #MG-10, by permission of the National Electrical Manufacturers Association.

The motor design factors that influence efficiency include: 1) the quality of the electromagnetic steel alloy used in the laminations; 2) the thickness of the laminations (both affecting the magnitude of the hysteresis and eddy-current losses in the steel core) and 3) the cross section size for the copper conductors (affecting electric resistance losses). One can refer to [Slemon] for an in-depth treatment of motor design considerations. In simple terms, to increase the efficiency of a motor at a given horsepower rating, additional wire copper and more, and possibly higher grade, steel lamination material must be used, with physical limits being reached short of 100 percent efficiency. Figure 2-3 is a plot of the full-load efficiency vs. the nominal horsepower of three-phase, 230/460 volt, 4 pole, 1,750 ± rpm, totally enclosed fan cooled (TEFC) motors.

Figure 2-3: Nominal Full-Load Efficiencies for Commercially Available Three-Phase Induction Motors, Compared to EPAct Minimum

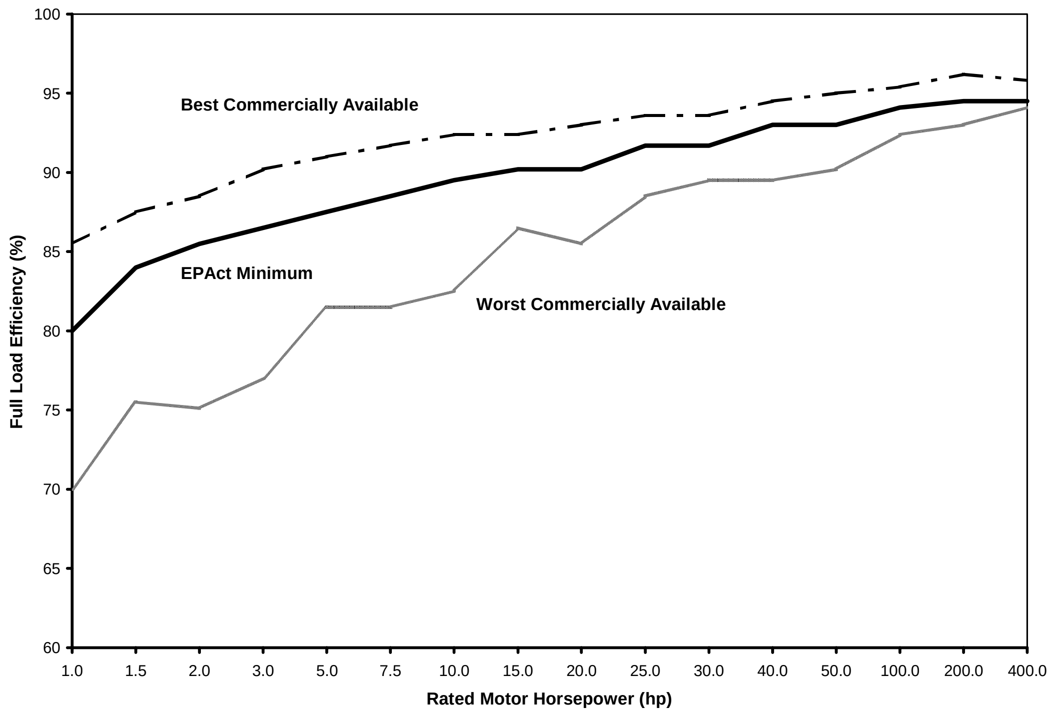


Figure 2-3 contains three curves: the curves for the highest and the lowest efficiency commercially available units [MotorMaster+ 3.0] and the curve representing the EPAct minimum efficiency. These curves illustrate several important issues:

- Motors are commonly available with a NEMA (National Electrical Manufacturers Association) nominal efficiency greater than the Energy Policy Act (EPAct) minimums, which took effect in October 1997.
- As the horsepower of the best commercially available motors approaches 150 hp and above, the efficiency curve begins to flatten. This suggests that the practical limit for efficiency and hp (with today's technology) is about 95 percent.
- Adoption of EPAct has had a significant impact on the efficiency of available motors. Average performance increases are in the range of 3 to 5 percent for the larger hp motors and 7 to 10 percent for the smaller motors. Efficiencies above 90 percent are available above 5 hp and routine above 20 hp.
- The current version of EPAct affects only those motors categorized as "General Purpose." Therefore, it is possible to have motors available on the market that are

below the EPAct minimum, as indicated by the bottom curve. This curve is composed of motors classified as "Special Duty."

Tables 2-1 and 2-2 (for open drip proof and totally enclosed fan-cooled motors, respectively) list the nominal full load efficiency and wholesale prices for a line of "standard" and "premium" efficiency motors. The difference in price and the number of full-load equivalent annual operating hours needed (for one and three year payback scenarios) are calculated. Figure 2-4 plots the operating hours calculated in Tables 2-1 and 2-2 with corresponding polynomial trendlines. The trendline plots indicate that the least operating hours required for a given payback period occurs between 10 and 100 hp. Below this level, the cost per horsepower is relatively high; above this level, the difference in efficiency between "standard and premium" is small and the cost per horsepower tends to increase. Over the 10 to 100 hp range, the incremental cost of the premium efficiency motor is a good investment, even for applications having only modest levels of annual operating hours. However, for replacing an existing standard efficiency motor with a premium efficiency motor, the payback period is 3 to 6 times longer and significantly reduces the number of attractive candidates for an "unforced" premium-efficiency motor retrofit.

Table 2-1: Price-Efficiency–Payback Comparison of Standard and High-Efficiency General Purpose Three-Phase Motors (Open Drip-Proof)

	Efficiency		Price			Annual Operating Hours for a	
Horse Power	**Std**	**High**	**Std**	**High**	**Delta**	**1 year payback**	**3 year payback**
1	0.825	0.855	$ 145	$ 160	$ 15	5,988	1996
2	0.84	0.865	$ 169	$ 184	$ 16	3,835	1278
3	0.865	0.902	$ 186	$ 200	$ 14	1,619	540
5	0.875	0.895	$ 207	$ 258	$ 51	6,692	2231
10	0.895	0.917	$ 359	$ 452	$ 93	5,813	1938
25	0.917	0.941	$ 772	$ 852	$ 81	1,940	647
50	0.93	0.945	$ 1,319	$ 1,437	$ 118	2,317	772
100	0.941	0.958	$ 2,444	$ 3,268	$ 824	7,322	2441
150	0.95	0.962	$ 4,184	$ 5,057	$ 873	7,427	2476
200	0.95	0.962	$ 5,287	$ 6,660	$ 1,373	8,761	2920
250	0.954	0.962	$ 7,100	$ 10,358	$ 3,258	25,050	8350

Source: Grainger, No. 389 (1998), p 23, pp 27-28
Note: All motors are Dayton Wattrimmer models Nameplate rpm: 1725-1775 rpm

Assumed Cost of Power: $0.08/kWh

The preceding statement applies directly to general-purpose motors purchased at typical commercial wholesale prices, in small quantities. The motors in the commercial sector that consume most of the motor energy—refrigerant compressors, air handlers, and refrigeration or air conditioning auxiliaries—are purchased on an OEM basis. This mix generally includes general-purpose motors used to drive pumps, blowers, fans, and open drive compressors. It can also include special configurations integrated with the product, e.g., motor stators and rotors assembled directly into a welded-hermetic or semi-hermetic refrigerant compressor. Although the data in Table 2-1, Table 2-2, and Figure 2-4 is generally representative of the price impact of premium efficiency at the end-user level, the specific application will determine cost-effectiveness.

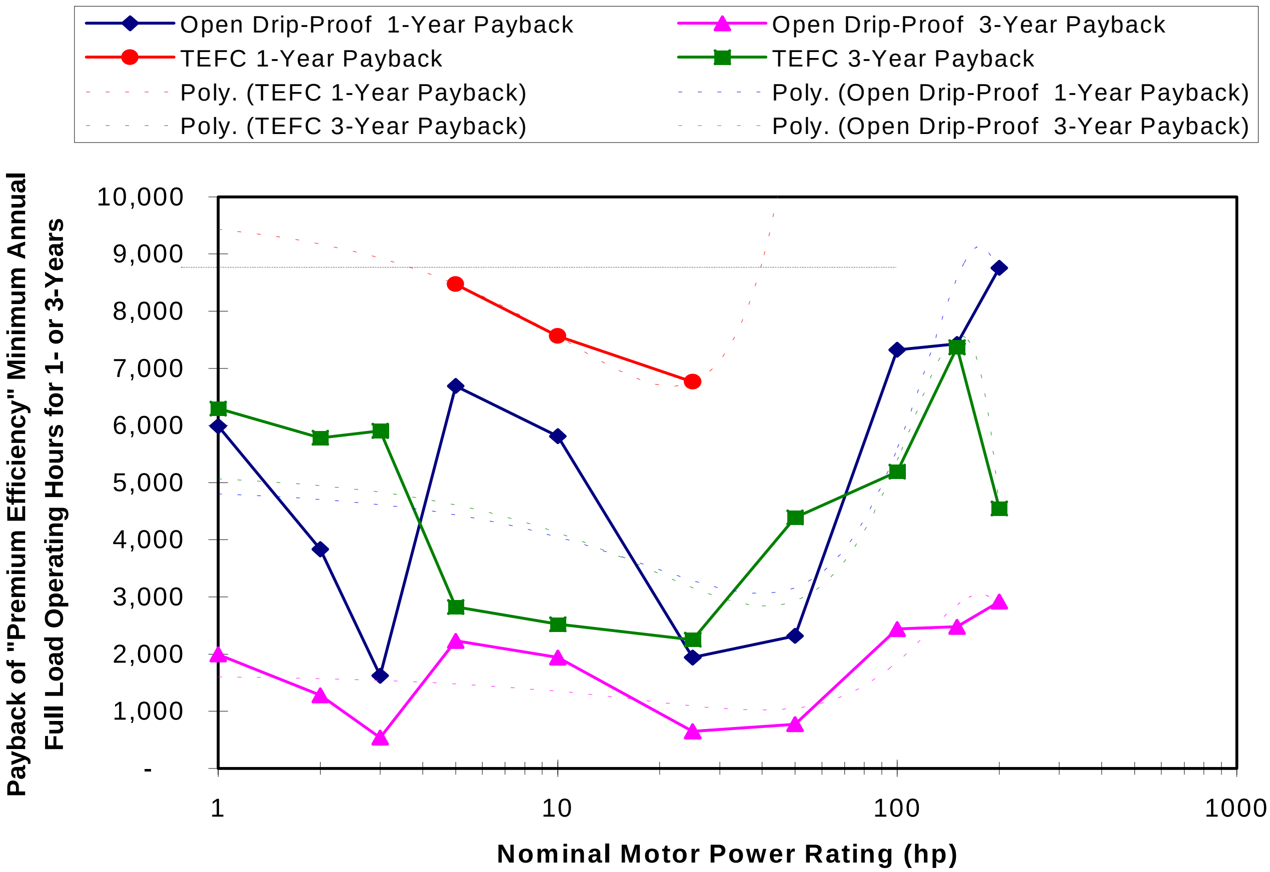
Table 2-2: Price-Efficiency—Payback Comparison of Standard and High-Efficiency General Purpose Three-Phase Motors (TEFC)

	Efficiency		Price			Hours for a	
Horse Power	**Std**	**High**	**Std**	**High**	**Delta**	**1 year payback**	**3 year payback**
0.5	NA	0.815	NA	$ 166	-	-	-
1	0.825	0.865	$ 150	$ 213	$ 63	18,893	6,298
2	0.84	0.865	$ 183	$ 254	$ 71	17,349	5,783
3	0.875	0.895	$ 213	$ 294	$ 81	17,715	5,905
5	0.875	0.902	$ 248	$ 334	$ 87	8,474	2,825
10	0.895	0.917	$ 460	$ 581	$ 121	7,564	2,521
25	0.924	0.936	$ 959	$ 1,099	$ 140	6,763	2,254
50	0.93	0.941	$ 1,558	$ 2,052	$ 494	13,171	4,390
100	0.945	0.954	$ 3,897	$ 4,825	$ 928	15,576	5,192
150	0.95	0.958	$ 6,183	$ 7,922	$ 1,739	22,099	7,366
200	0.95	0.962	$ 7,382	$ 9,521	$ 2,139	13,648	4,549
250	NA	0.962	NA	$ 11,945	-	-	-

Source: Grainger, No. 389 (1998), pp 25-26, pp 30-31

Note: All motors are Dayton Wattrimmer models Nameplate rpm: 1725-1775 rpm

Figure 2-4: Annual Operating Hours Corresponding to One- and Three-Year Payback for Premium Efficiency General Purpose Three-Phase Motors



Note: The minimum annual full load operating hours required for a 1-year payback for a 1, 2, 3, 50, 100 and 200 hp TEFC 3-phase motor exceeded 8,760 hours (maximum hours in a year).

2.1.2 Single-Phase Squirrel-Cage Induction Motors

Single-phase, 60 Hz, alternating current is generally available for all residential and commercial buildings, typically at voltages of 115 VAC and 208 VAC or 230 VAC. Typically, 115 VAC circuits are used to power motors up to 2 hp and 208/230 VAC circuits power motors up to 5 hp. Larger power outputs are seldom required in residential applications. As discussed earlier, three-phase power is typically available in commercial buildings to operate motors above 5 hp and many motors whose output is 5 hp or less.

The basic principal of operation of a single-phase SCIM is similar to a three-phase induction motor. A rotating magnetic field is easily established with three-phase excitation of motor windings as described in the preceding subsection. It may be shown that in a single-phase induction motor two counter-rotating fields are produced which develop equal and opposite rotor torque components when the motor is at standstill. However, if means are provided to urge rotation in one direction or the other, net torque will be developed to sustain the rotation and drive the attached load. It is of interest to note that while the electromagnetic torque acting on the rotor of a three-phase motor is relatively smooth and free from pulsating disturbances this is not the case in the single-phase motor. In this instance, the torque may pulsate from zero to a maximum value at twice the power line frequency—e.g., 120 Hz. In most applications, this is of little consequence as the inertia of the motor and the driven load act to smooth out the torque pulsations. Efficiencies of single-phase motors are approximately 10 percent less than three-phase units.

The basic construction of the single-phase induction motor includes a rotor and stator; each built up of a stack of electromagnetic grade steel laminations as previously described for the three-phase motor. The “squirrel-cage” rotor has a series of aluminum bars cast lengthwise into the rotor laminations. These bars are connected with rings located at each end of the stack. The stator laminations contain a series of slots for the windings that are aluminum or copper wire. Two sets of windings are provided, at a 90°-phase difference. The “main” or “run” winding operates directly from line current, and stays always energized as long as the motor is running.

Single phase motors are categorized according to the way the “start,” “secondary,” or “auxiliary” winding is utilized for starting the motor and then running it at normal speed. The following are widely used single-phase motor categories:

- The Split-Phase or Resistance Start/Induction Run (RSIR) Motor—This configuration is the lowest cost. The start winding has a higher resistance-to-reactance ratio than the main winding achieved by using a relatively small diameter wire. This reduces both the amount and the cost of the copper in the start winding and the space taken up in the stator slots by this winding.

- The Capacitor Start/Induction Run (CSIR) Motor—This configuration is a low-efficiency motor that provides higher starting torque than the RSIR motor.

- The Permanent Split Capacitor (PSC) Motor—This configuration has a high potential efficiency, depending on the design. It could take one of two forms:
  - No start assist beyond the run capacitor, which leads to a weak starting torque
  - With resistance start assist device—a typical start assist device being a positive temperature coefficient resistor (PTCR)

- The Capacitor Start/Capacitor Run (CSCR) Motor—This is an efficient run configuration with a large capacitance at start-up providing a large starting torque. The start capacitance is typically three to five times the size of the run capacitor, but can be packaged compactly because continuous operation (and the resulting heat dissipation) is not a consideration.

RSIR and CSIR motors use the secondary winding for starting only, the capacitor start version providing higher starting torque. The secondary winding uses a much smaller diameter wire energized for a limited time without overheating and automatically disconnected after start up by a centrifugal switch. The RSIR motor is very low in cost, but is inherently limited to an 8 to 10 percent lower efficiency than PSC motors. In PSC and CSCR motors, the secondary winding continues operating when the motor is running. The capacitor in series with this winding shifts the phase of the input voltage approximately 90°, so the two windings together create a rotating magnetic field. The benefits achieved by PSC and CSCR motors are the suppression of torque pulsations and the improved utilization of both the windings and the iron in the motor. These benefits increase the efficiency and the power factor of the motor, but at an added cost associated with the capacitor.

Motor efficiencies are improved by:

- Using additional material (increasing the stator and rotor lamination stack length and increasing the winding conductor cross-section—by using larger diameter wire or increasing the number of parallel strands comprising a conductor)
- Using low-loss steel for the laminations
- Using thinner laminations

2.1.2.1 Refrigerator Application of the Single-Phase SCIMs

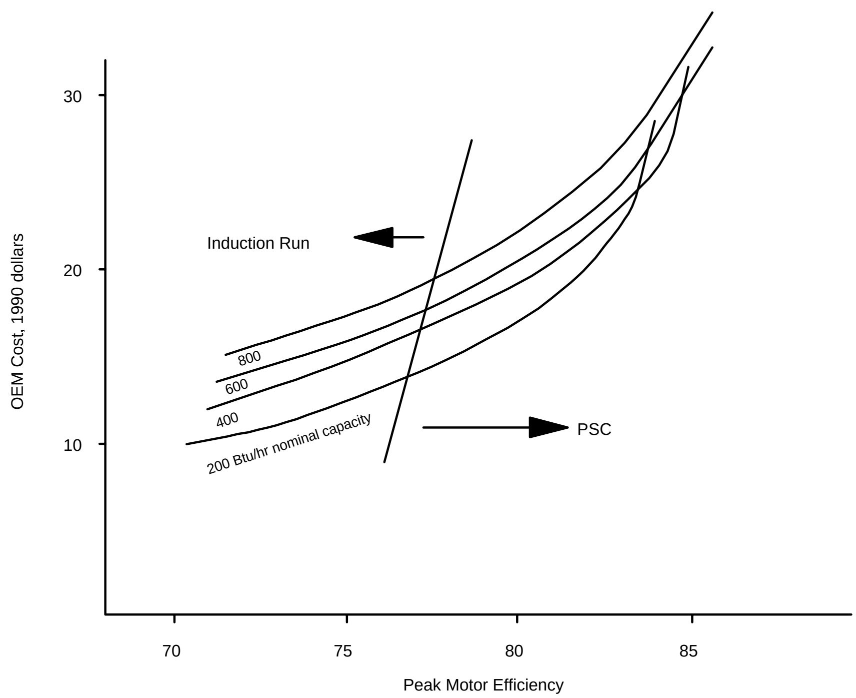
The compressors used in domestically produced and marketed domestic refrigerators and freezers in the United States are powered using two-pole AC SCIMs that operate on normal household line power, i.e., 115 VAC, 60 HZ, 1 phase. These motors run at constant speeds of approximately 3,500 rpm. In addition to running the compressor over the normal range of loads, the motor must provide an adequate starting torque, since small, single cylinder compressors are difficult to start.

Figure 2-5 plots the estimated cost per motor of single-speed induction motors vs. efficiency for motors sized for compressors having nominal capacities between 200 and 800 Btu/hr. The costs are based on the OEM price paid to the motor supplier by the compressor manufacturer for production level quantities of the motors. For the smaller motors, the maximum physically attainable efficiency is lower than that for the larger motors, and consequently, the cost-efficiency curves cross over.

From Figure 2-5, it is apparent that:

- High motor efficiency (with a peak value near 85 percent) is technically feasible in any compressor capacity of interest, once all of the aforementioned measures to improve efficiency have been applied.
- The cost of attaining the highest efficiency is significant, qualitatively. For the smaller compressor capacities, the highest-efficiency motors could cost up to two to three times more than motors currently used.

Figure 2-5: OEM Cost of Single-Speed Induction Motors for Hermetic Refrigeration Compressors Versus Motor Efficiency and Compressor Capacity



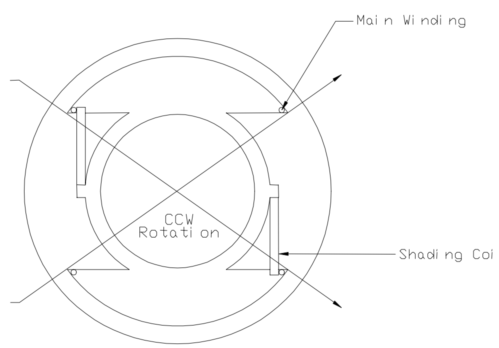
OEM Cost: Price paid by each compressor manufacturer to the motor manufacturer for mass production quantities. Includes cost of required relay, capacitor, etc.
Efficiency: Not accounting for any mechanical losses
Source: Data provided by GE Motors, 1/12/90, and informal discussions on OEM cost levels with OEM suppliers of motors and manufacturers of refrigeration compressors

Only a few manufacturers produce compressor motors for refrigerator/freezer (R/F) applications. Americold, Matsushita, and Embraco make them for their own compressors; Americold supplies compressors primarily to White Consolidated Industries. GE makes these motors for sale to all compressor manufacturers. Tecumseh manufactures most of the motors for their small compressors. A.O. Smith and Copeland make motors in the 1/2 and integral horsepower sizes; Copeland builds them only for their own compressors.

2.1.3 Shaded-Pole Induction Motors

Shaded-pole induction motors contain a rotor similar to the conventional induction motor. The shaded-pole motor has a portion of its main pole area circled by a short-circuited copper ring called a shading ring. Induced currents in the shading coil cause a phase lag between the flux in the shaded portion of the pole and the flux in the non-shaded area, producing a rotating field which enables starting. These motors are typically used in fractional horsepower sizes, primarily in very small (< 1/10 hp) sizes and have a particularly poor efficiency (10 to 35 percent). Major appliance applications include refrigerator fans and air conditioning condenser fans. Other applications include window fans as well as myriad other applications. In residential-sector appliance applications (discussed in Section 3.1), the implementation of NAECA standards has motivated the replacement of shaded-pole motors with higher-efficiency PSC motors or with electronically commutated permanent magnet motors, discussed in Section 2.2.2.

Figure 2-6: Shaded-Pole Motor



2.1.4 Universal AC/DC Motors

A universal AC/DC motor is essentially a brush type DC motor with a wound field and a wound armature. They are commonly used for application speeds higher than 3,500 rpm (2-pole induction motor speed). The major application is for vacuum cleaner blowers, which generally operate between 15,000 and 20,000 rpm. Other applications include power hand tools, where motor speeds greater than 3,500 rpm are needed or desirable due to the increased power density. Note that universal AC/DC motors require no auxiliary windings, capacitors, or relays to control them.

High-efficiency brushless DC motors could also provide the high speeds required in these applications, but only at a significantly increased motor cost as well as additional cost for the power electronic circuitry required for their operation. Brush-type permanent magnet motors are a better choice for battery powered cordless power tools. Like the universal motor, these motors offer high speed and high power densities in an inexpensive package. The peak efficiency of brush-type permanent magnet motors tends to be in the 60 to 70 percent range.

The duty cycle of universal motor driven appliances tends to be low. They account for an insignificant fraction of motor energy consumption in both the residential and commercial sector.

2.1.5 Two-Speed Motors

Two-speed induction motors provide a method for potentially improving refrigeration, air conditioning/heat pump, and air-distribution system performance. The performance increases because frequent on/off cycles at full power can be replaced with long periods of half-speed operation, which leads to reduced evaporator and condenser coil loading. There are two basic designs used to achieve two-speed motor operation; the first employs a so-called *consequent pole* winding and the other provides the motor with separate sets of two-pole and four-pole windings. The consequent pole arrangement is simpler, more compact, and has a lower cost, but also has an inherently lower half-speed efficiency for a fractional horsepower motor.

As an example, the performance and cost characteristics of a two-speed motor used for an 800 Btu/hr refrigerator/freezer compressor and efficiency-optimized for low speed are:

- 80 percent efficiency at full-speed
- 70 percent efficiency at half-speed
- Cost close to that for a maximum efficiency single-speed motor (Figure 2-5, Table 2-3)

These efficiency values represent the estimated highest levels attainable for this type of motor, with an output needed to operate an 800 Btu/hr compressor. There are no two-speed motors currently in production for this application. Cost and efficiency estimates are based on presales preliminary design studies of a major supplier, and are subject to considerably more uncertainty than the corresponding cost-efficiency curves in Figure 2-5 for single-speed motors.

Two-speed motors are not available from many U.S. motor manufacturers in the above size range. The technology exists to build two-speed motors, but there is not a large enough market for them now. Fans and pumps in integral horsepower sizes typically use two-speed motors. Some residential central air conditioning applications in the

1.5 to 5 hp range and larger use two-speed compressors, including Bristol (produces the two-speed compressor), Copeland (produces the two-speed compressor), Lennox, Goodman (Janitrol), and Carrier.

2.2 Variable-Speed Drive and Motor Technologies

Electronically variable speed drives (VSDs) allow motors to operate over a continuously variable speed range, and the maximum speed is not limited to 3,500–3,600 rpm limit for a two-pole, 60 Hz induction motor. The variable-speed drive is an electronic unit that converts fixed frequency—fixed voltage input power to adjustable voltage and frequency output power, which enables the associated motor to run at a variable speed. VSDs are designed to accommodate various input power formats—e.g., 115 VAC, 60 Hz, single phase or 208, 230 or 460 VAC, three-phase. In the context of refrigeration, air conditioning/heat pump, and air distribution applications, potential benefits of variable-speed motor capability include the following:

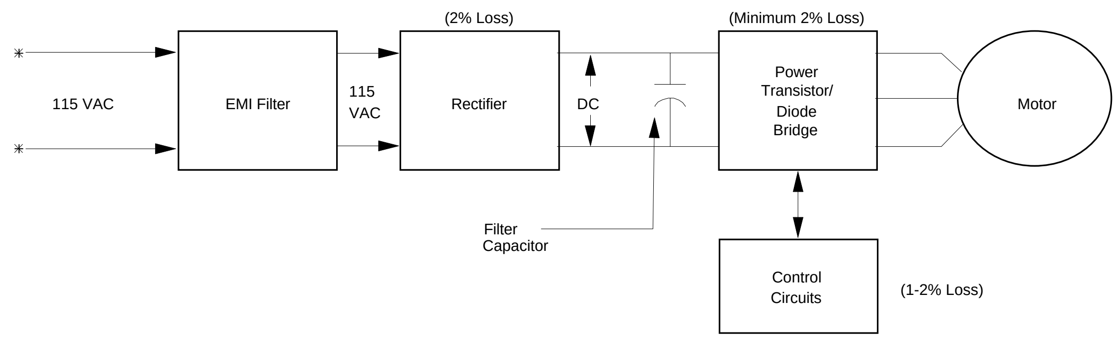
- Continuous and close load following to achieve minimal deviation from temperature set point
- Rapid ramp up from a temperature set-back or ramp-down to a set-back
- Reduced heat exchanger loading enabling use of smaller, lower-cost units
- Attainment of motor speeds greater than 3,600 rpm, thereby allowing reduced equipment size and cost
- Reduced on/off cycling losses
- Reduced average air and fluid moving power

Variable-speed drives are either being commercially produced, or are currently under development, for the following motor categories potentially applicable to residential or commercial equipment:

- Three-phase SCIMs
- Electronically commutated permanent magnet rotor motors (ECPMs)
- Switched reluctance motors (SRMs)

The basic electronic hardware configuration of variable-speed drives used to operate each of these motor classes is very similar. Figure 2-7 is a simplified block diagram depicting the generic functions of a typical variable-speed drive for any motor type. After passing through an EMI filter (to minimize coupling of internally generated radio frequency noise to the input AC line), the input AC is rectified and filtered to DC form. Output power transistors (typically “Insulated Gate Bipolar Transistors,” or IGBTs) modulate the DC power by switching ON and OFF with controlled frequency and duty cycle. This modulation provides the motor windings with an excitation waveform appropriate for the particular type of motor. In general, to drive any of the three motor types over a wide speed range requires varying the motor input voltage and frequency in a coordinated fashion.

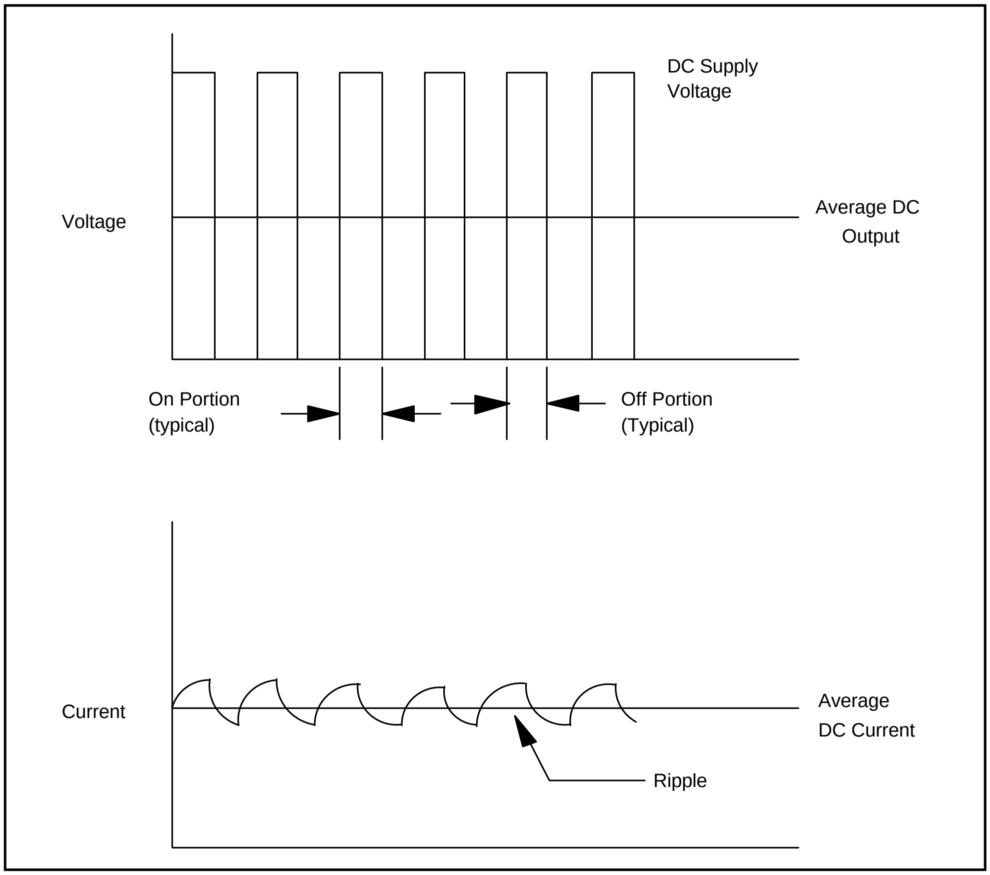
Figure 2-7: "Generic" VSD Block Diagram



Source: GE Motors, 1990; Toshiba (a), (b); Lloyd, 1982

Modulation of the DC supply power for induction motors produces an output voltage having a sinusoidal waveform. SRMs and typical ECPMs are excited by quasi-rectangular voltage waveforms while high performance ECPMs used in industrial servo applications may require sinusoidal excitation. The use of a pulse width modulation (PWM) technique produces this voltage modulation. Figure 2-8 illustrates the operation of PWM to vary the amplitude of a quasi-rectangular input voltage to an ECPM or SRM during a typical half cycle of the excitation waveform. The output transistors are switched ON and OFF at a much higher frequency than that of the required winding excitation waveform. The output voltage applied to the winding is varied from 0 to the DC supply voltage by changing the length of the ON time of the output transistors from zero to the full period of the high frequency PWM square wave. The inductance of the motor winding stores energy in excess of the average DC voltage during the pulse ON time, and releases the energy during the pulse OFF time to maintain a continuous current flow. During the OFF period of the high frequency PWM square wave, the winding current is carried by "freewheeling" diodes which bypass the power transistors.

Figure 2-8: PWM Operation for Varying Output Voltage to a DC Motor



For motors that require sinusoidal excitation (e.g., the SCIM), the PWM duty cycle (ratio of ON to OFF time) is continuously varied. This causes the *effective* value of the resulting pulse waveform to closely follow a sinusoid of the required amplitude and frequency. While the PWM motor voltage applied to the motor leads appears as a train of pulses the winding current is nominally sinusoidal due to the smoothing action of the winding inductance as explained previously for the case of quasi-rectangular excitation. The configuration of the output switching transistors in a *bridge* circuit permits generation of *bipolar* (i.e., plus and minus) output voltages as required for SCIMs and most ECPMs. Somewhat simpler *singular-polar* switching circuits may be used for some SRMs and ECPMs.

The latest VSD designs for SCIMs and ECPMs employ IGBT switching bridges integrated in a single package along with the freewheeling diodes. Illustrative suppliers are International Rectifier, Motorola, Semikron, and Powerex. Some bridge packages also provide the *gate driver* circuitry required to couple the output transistor bridge with the control unit and may include the input rectifier diodes. For lower power, very high volume requirements (e.g., fan motors) control circuitry may also be integrated with the bridge and gate driver package as a one chip “solution.” Highly integrated IGBT bridge and driver packages are available even at 100 hp and higher levels from suppliers such as Semikron and Powerex. Some units include built in protection circuitry as well as current and voltage sensors.

While SRMs are beginning to find high-volume appliance applications, such as the Emerson Electric motor for the new front loading Maytag washing machine, multi-IGBT packages optimally configured for SRMs are not being advertised in the trade literature at this time. However, vendors may be supplying these on an OEM basis. Hewlett Packard computer plotters use “application-specific integrated circuit” (ASIC) drivers for relatively small SRMs.

Control of the power transistor switching bridge is now being implemented almost exclusively by digital means. The high speed processing capabilities of digital signal processors (DSP) widely used for communications applications are being used for highly cost-effective implementation of sophisticated motor control policies which avoid the need for feedback sensors and minimize motor cost. DSP control will also permit cost-effective implementation of actively controlled input rectifier circuits which can reduce input current harmonic distortion–a matter of growing concern as the use of variable-speed drives becomes more wide spread. Analog Devices and Texas Instruments for example have introduced low cost DSPs with on-board PWM output circuits that specifically target high volume, embedded motor drive applications such as domestic appliances. Analog Devices’ motor control DSPs also feature on-chip multi-channel analog-to-digital (A/D) converters to further reduce the cost of assembling an embedded motor controller. In cost sensitive embedded motor drive applications the DSP may also support system control functions such as fault detection/protection, operator input/output (e.g., set temperature setpoint and report current temperature) or outer loop control (e.g., control of compressor speed according to operating conditions and setpoint).

There is a variety of other techniques for changing motor speeds, such as electrically or electronically, that are currently in use or under development. Those in use are generally for specialized industrial applications, usually at power levels greater than 25 hp. The three variable-speed drive/motor combinations covered in this section represent technologies that have been developed, or are undergoing development for mass market applications and have the best potential for low cost production.

As the number of variable-speed drives in service increases, regulations are likely to come about requiring means to suppress power line harmonic currents drawn by the input rectifier section in addition to higher frequency EMI filtering. This type of regulation is already in place in Europe for electronic motor drives drawing more than

200 watts from the AC line. Harmonic current suppression adds components and cost to the variable-speed drive, and may slightly degrade efficiency.

Subsections 2.2.2 to 2.2.4 present brief descriptions of the operating principle of each of the different motor types with a variable-speed drive, and also include a brief summary of the current commercial status for each of the three VSD-motor technologies.

2.2.1 Efficiency Issues and Opportunities With Variable-Speed Drives

The overall efficiency of a variable-speed motor and drive (shaft power output divided by the AC line electric power input) is the product of the electronic drive efficiency and the motor efficiency. Electronic efficiencies for the three types of variable-speed drive are nearly identical, because the configuration of the power electronics (EMI filter - rectifier - filter - output transistor/diode bridge) is essentially the same for each. The efficiency decreases with decreasing output voltage (and motor speed) and, to a lesser extent, with decreased load (torque) and output current.

For fractional horsepower motors, the inherent efficiency of the three motor types (three-phase SCIM, ECPM, and SRM) are offset from each other by small increments:

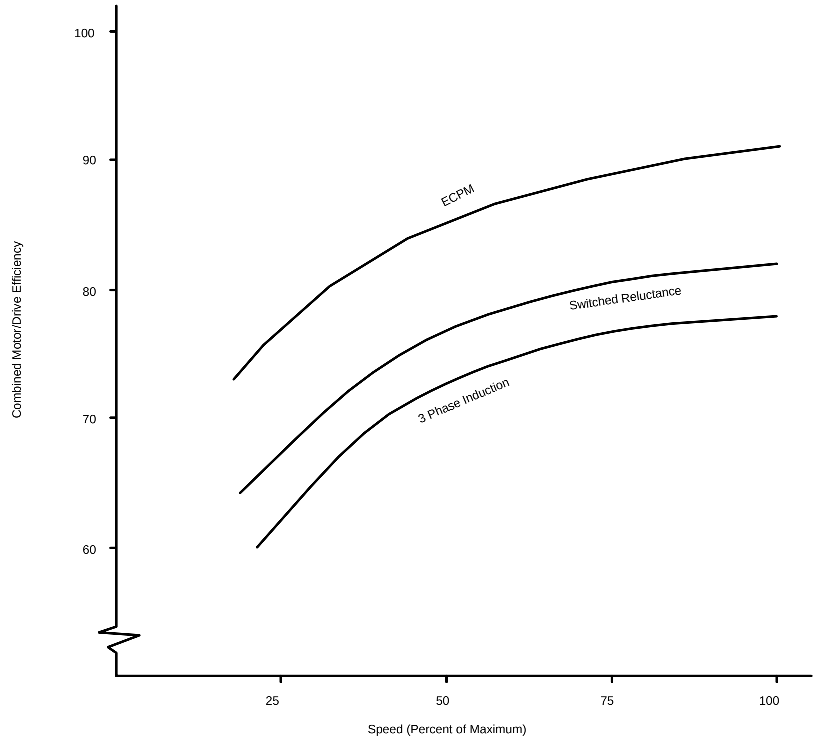
- ECPMs have the highest efficiency, approaching a 95 percent level (for the motor only), because the permanent magnet rotor supplies the field, incurring no electric resistance losses. ECPMs incur only minor ripple loss from PWM operation at intermediate input voltages and speeds.

- SCIMs are approximately five percentage points lower in efficiency than ECPMs. The PWM waveform causes an additional 3 to 5 percent efficiency degradation at a reasonably high PWM frequency (10 kHz) and a 5 to 10 percent degradation at a low PWM frequency (1 to 2 kHz) due to the higher harmonics of the pulsed waveform.

SRM efficiencies fall in between the other two types, but may require higher quality steel core laminations, smaller air gaps and consequently tighter manufacturing tolerances and possibly higher quality bearings. The SRM drive may have requirements that are more demanding on the timing of excitation waveforms.

Figure 2-9 plots overall motor/drive efficiency vs. motor speed for each of the three basic motor types (applicable to motors between 1/10 and 1/3 hp output).

Figure 2-9: Comparison of Variable-Speed Drive/Motor Efficiencies (Fractional Horsepower)



Source: Arthur D. Little estimates made from discussions with the Variable Speed R & D Group of GE Motors, 1990

2.2.2 ECPMs

Electronically commutated permanent magnet rotor motors, also commonly referred to as “brushless DC” motors (if excited with quasi-rectangular current waveforms as is often the case for non-servo applications), have a permanent magnet rotor and (usually) three sets of stator windings. As the rotor moves, the stator windings are commutated, i.e., switched in phase with the permanent magnet poles on the rotor. To control commutation timing, rotor position is sensed and fed back to the ECPM variable-speed drive and used for timing the switching of the output power transistors to control the current in the motor windings. In ECPMs, Hall effect sensors in the motor sense the rotor position. An additional set of lead wires is required to connect the sensors to the controller.

An alternate commutation controls technique, developed and used by GE, senses the back EMF in the OFF winding, and commutates on an initial rise of the EMF. The advantages of this technique are twofold. First, they include the obvious cost savings associated with eliminating Hall effect sensors and lead wires. Second, for hermetic compressors, the reduction in the number of wires to three power conductors that must penetrate the hermetic shell of the compressor reduces cost and improves reliability. The economic and reliability advantages of a "sensorless" VSD have motivated the continuous improvement of this technology by many university investigators and manufacturers for ECPM, SCIM, and SRM applications. Moreover, the recent availability of low-cost VSD-specific DSP chips by Analog Devices, Texas Instruments and others has facilitated cost-effective implementation of ever more sophisticated and capable sensorless control algorithms.

The basic operational characteristic of the ECPM is similar to a conventional brush-type permanent magnet DC motor (speed proportional to the DC supply voltage, and torque proportional to the current). To provide for variable-speed operation, the ECPM controller must vary the effective DC supply voltage to the motor, as well as providing for correctly timed commutation. Pulse width modulation is a cost-effective and efficient means of varying the DC voltage supplied to the motor (Figure 2-8), because the high speed PWM switching is accomplished by the same output transistors used for commutation. The effect of the high speed PWM switching on the motor is a low-level ripple in the DC voltage and current to the motor. This results in a modest increase in joule heating (I^2R) losses in the stator windings, decreasing the motor efficiency by about one percent.

The high efficiency of ECPMs is due to two basic attributes of the motor:

- The permanent magnet rotor supplies the field, requiring no input power, unlike the induction motors and wound field type DC motors.
- The placement of the windings on the stator allows room for more winding wire cross section, and the consequent achievement of a lower I^2R copper loss than in a typical brush type DC motor.

Permanent magnet materials widely used for ECPM rotors include:

- Ferrite
- Neodymium-Iron-Boron (NdFeB)

Ferrite magnets are relatively low in magnetic field strength and cost. NdFeB magnets provide much stronger fields, allowing more power output for a given motor frame size and efficiency requirement. The cost of NdFeB magnets, however, is considerably higher, so that currently the least costly motor uses a ferrite rotor.

OEMs are the primary supply source for ECPMs in the market. The most attractive applications are small HVAC and refrigeration equipment fans, with power requirements less than 1 hp. The smallest size offered by GE includes a 4W-shaft output, used typically for domestic refrigerator/freezers. Small sizes are the best justification for the cost premium of the motor where commercially available alternatives have a rather low efficiency. The cost of the electronic power supply/controllers (i.e., VSD) becomes prohibitive for larger motor sizes. Fan applications are particularly attractive to the OEM because product engineering costs are small (e.g., compared with compressor applications). ECPMs in fractional hp are currently being developed for "drop-in" use for fan applications.

2.2.3 SCIMs With Variable-Speed Drive

Essentially, conventional three-phase SCIMs operate in a variable-speed mode if variable frequency and variable voltage power energize them. Motor speed will nominally vary directly with power frequency and typically, the applied voltage amplitude is adjusted to follow the frequency variation. This mode of operation is referred to as "constant volts per Hz" and is widely used in applications such as variable-speed fan or pump drives which do not require rapid control of speed or shaft position control. In more demanding applications such as machine tool motion control, more sophisticated frequency and voltage control policies are employed.

The generic variable-speed drive previously discussed and depicted in Figure 2-7 is suitable for use with an SCIM. However, the SCIM requires excitation by sinusoidal voltages rather than quasi-rectangular ones suitable for the brushless DC motor version of the ECPM. As explained previously, SCIM excitation voltages, which have an effective sinusoidal form, are synthesized from the DC supply of the VSD by appropriate PWM control of the output switching transistors. A VSD configured for production of sinusoidal output voltages is often referred to as a "PWM inverter" or simply an "inverter."

Compared to ECPMs, PWM inverter-driven, fractional horsepower, SCIMs are inherently limited to efficiencies that are 5 to 10 percentage points lower. There are several major reasons for this:

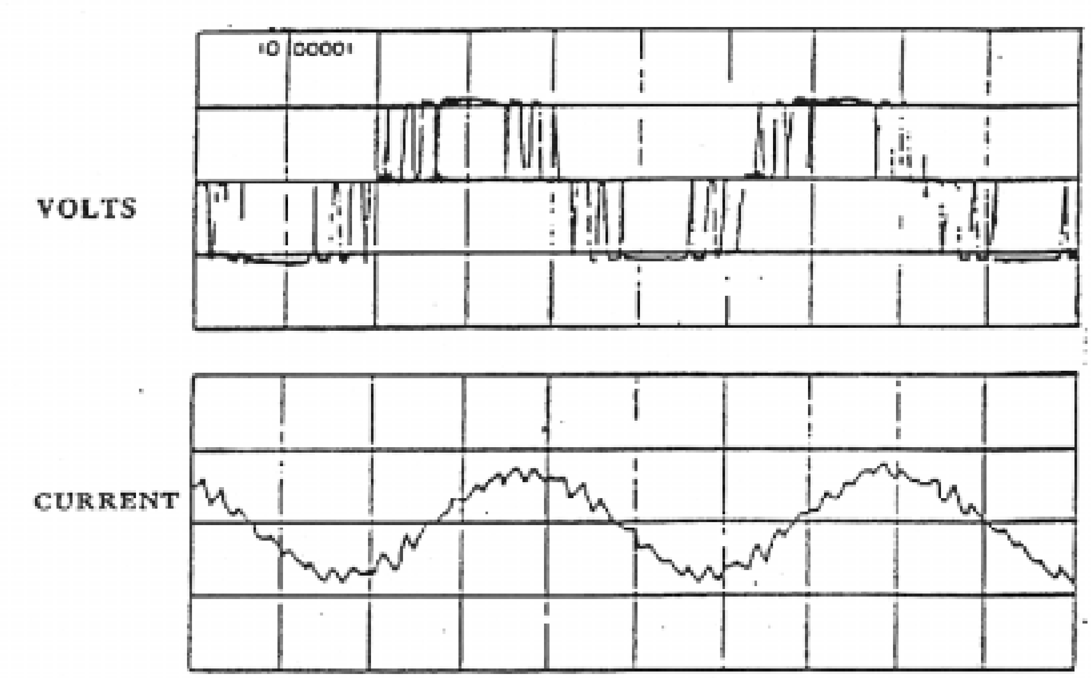
- SCIM efficiency is a few percentage points below the ECPM, due to the reasons discussed in 2.2.1.

- The SCIM excitation voltage produced by the PWM inverter is not truly sinusoidal but rather consists of a train of variable width, constant amplitude pulses, which have an effective value approximating that of a sine wave. This approximation results in some degradation of motor efficiency, because of the ripples and harmonics associated with PWM variable-width pulses.

- PWM switching frequency is not precisely synchronized with the timing of the output waveform. This results in some output waveform asymmetry, which increases its harmonic content.

The net result is a lower motor efficiency, by 3 to 5 percent for high PWM frequency (e.g., 10 kHz), and by 5 to 10 percent for low PWM frequency (e.g., 2 kHz).

Figure 2-10: Voltage and Current Output of a PWM Inverter (approximate PWM frequency: 1.1 kHz)

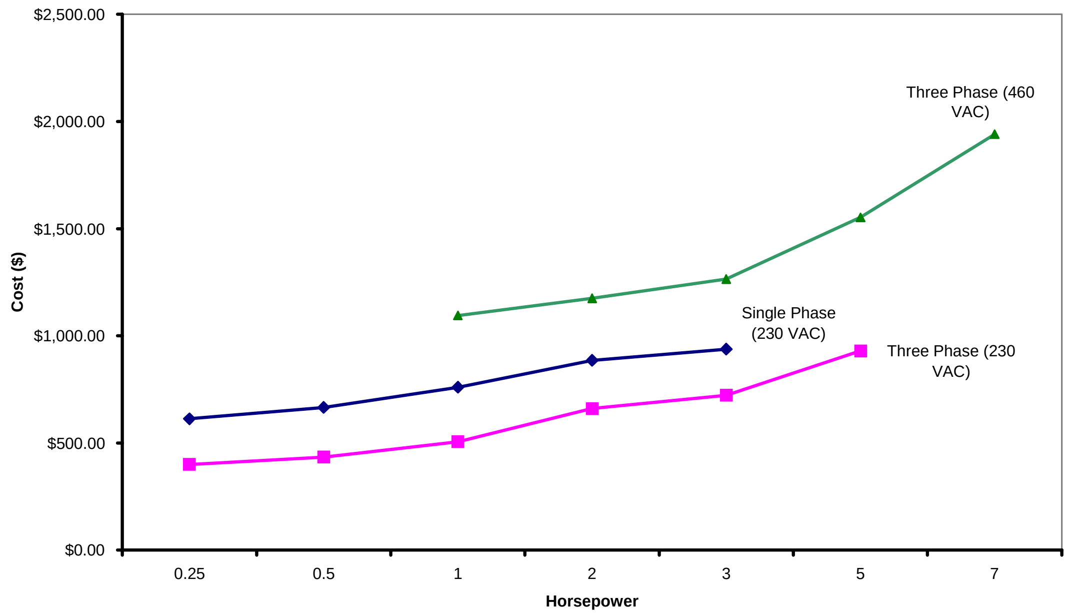


Source: Toshiba product literature

The efficiency loss is partially offset due to a small advantage in SCIM cost over that of an equivalent which, in turn, is attributable to the difference in materials cost between a squirrel cage rotor and a permanent magnet rotor.

PWM inverters are widely used in the United States for three-phase motor speed control in industrial applications, primarily in integral horsepower and larger output sizes. Larger motors that use inverters in the 5 to 50 hp range are primarily of interest for variable air volume applications within the air handler. Figure 2-11 summarizes the various costs of both single- and three-phase PWM inverters based on horsepower and voltage. This figure suggests that as the motor size increases, the cost for variable-speed control also increases. As of 1996, U.S. sales of variable-speed drives for induction motors were only about 100,000 units per year (5 percent of AC industrial motor sales), but were increasing at an average annual rate of 35 percent (based on value) since 1988[1].

Figure 2-11: PWM Inverter Costs



Source: Grainger, 1998-1999, Catalog No. 389

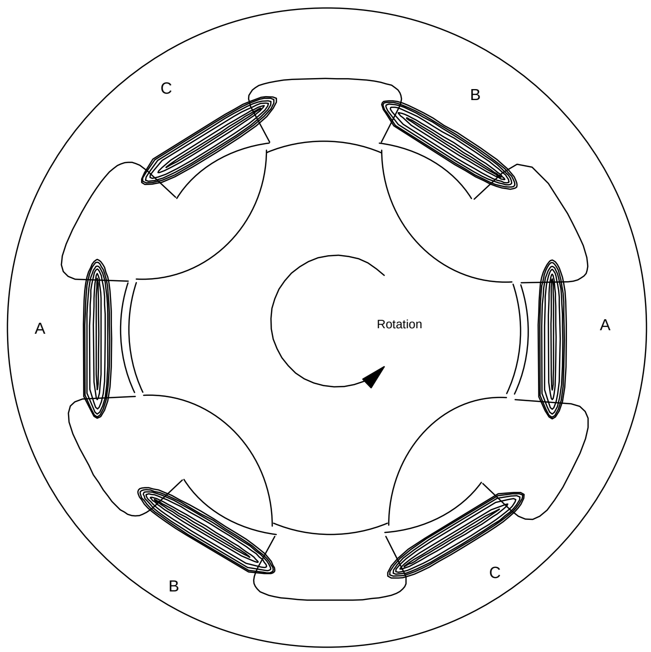
2.2.4 SRMs

The SRM concept is quite old and has been reported to predate that of any other electrical motor type. However, the inferior performance of the early switched, as well as non-switched, reluctance motors did not permit them to compete with other motor alternatives. Modern SRM drive *systems* (i.e., SRM + VSD) represent a relatively new technology, enabled by advances in power and control electronics technology. Advanced software tools are responsible for the success of modern SRM designs. These tools facilitate adjustment of the highly non-linear SRM magnetic circuit as well as exciting current waveform and timing to optimize torque production for designs bounded by dimensional and efficiency constraints. As shown in Figure 2-12, the motor consists of a rotor and stator, each with a different number of discrete, equally spaced poles. The rotor construction includes a stack of thin steel laminations provided with individual pole protrusions located on the inner diameter as shown in the Figure. In contrast to the SCIM motor, the SRM motor contains no conductor bar nor induced

[1] DOE, 1996; page 22.

current in the rotor, and no rotor magnets are required. The stator construction includes a stack of thin steel laminations with individual poles that are fitted with wound coils. An encoder in the motor housing senses the rotor position and pulses of current are applied to the stator poles to match the rotor angle.

Figure 2-12: Simplified Schematic of an SRM Configuration



At rotor position and rotation direction shown:

- Winding A has just been switched off
- Winding B is off
- Winding C was just switched on

As indicated in the Figure, the timing of the pulses is such that each stator pole energizes as each rotor pole approaches and de-energizes as the rotor pole achieves full alignment. The “generic” drive of Figure 2-7 is applicable, with PWM used to synthesize the quasi-rectangular winding excitation waveforms required for optimal operation of the SRM.

SRMs have several unique attributes that are potentially advantageous, depending on the application:

- They have very high low-speed torque.

- The rotor uses no conductor bars or permanent magnets, and hence the potential motor cost is lower.

- The stator coils can be automatically and precisely wound on bobbin forms and then fitted over the core pole protrusions (relative to “scramble” or “random” wound coils fitted to small ECPMs or SCIMs, stator coils manufactured and installed in this fashion have the advantage of high “fill factor,” minimal turn-to-turn voltage stress, and robust insulation from the core steel).

- Overall motor + drive system efficiency can approach that of the ECPM.

However, to realize higher efficiencies, a very precise timing of the energizing and de-energizing of the stator pole windings is required. In addition, the use of very-low-loss (high-cost) lamination materials is needed, limiting the potential cost benefits. Other barriers that the SRM must overcome to displace ECPM and SCIM alternatives are:

- Requirement for greater manufacturing precision, since the SRM typically requires a smaller mechanical gap between the rotor and stator
- Requirement for a better class of bearings to accommodate reliable operation with a relatively small mechanical clearance gap
- Manufacturing economy for SCIMs attained over an experience period of more than 90 years
- More challenging design due to highly non-linear magnetic circuit operation and requirements for precise timing of excitation waveforms
- Relatively high level of acoustic noise generated by magneto-strictive forces acting on the laminations as well as aerodynamic interaction of the salient rotor and stator poles

High torque features do not represent the same degree of advantage for compressor motor applications that they do for vehicle traction drives or direct drives of washing machine agitators for example.

Modern SRM technology was developed at Leeds and Nottingham Universities in England and licensed by Switched Reluctance Drives, Ltd. in Leeds, England. One noteworthy high volume application in the United States is the SRM VSD manufactured by Emerson Electric for an advanced, direct-drive front loading domestic washing machine. Another is a smaller SRM, manufactured by Warner Electric, used as a cruise control servomotor in Ford products. Hewlett Packard also has been using large numbers of SRMs in computer plotters. Emerson Electric reported that it would soon launch a line of integral horsepower SRM VSDs for industrial applications.

SRMs are being investigated for use in electric vehicles for traction drives, where advantageous SRM characteristics are high torque at low speed for good acceleration and good efficiency at higher speed and low torque cruising conditions. The potential for lower cost than ECPM and SCIM VSD solutions is another important advantage for traction drives. In general, SRM VSD technology has great potential but is at an earlier stage of development and commercialization than ECPM and SCIM alternatives.

2.3 Variable-Speed Motor/Drive Costs—Refrigerator Compressor Motor Example

This subsection addresses prospective mass-production costs of application-specific, “embedded” variable-speed drives using a refrigerator compressor as an illustrative example.

Estimates of eventual mass production costs for application-specific, embedded, variable-speed drives are subject to considerable uncertainty. Currently, there are relatively few instances of U.S. mass production of such drives and therefore, an absence of OEM sales data upon which to base cost estimates. In general, OEM prices and manufacturing costs are commercially sensitive information which manufacturers are reluctant to disclose. General Electric is marketing variable speed, electronically commutated motors, targeting mass market applications - appliances, air conditioning, and automotive—representing total motor/drive system sales approaching 50,000 units annually. Applications range from 5 hp heat pump compressor drive motors to one half hp indoor air blower motors for central air conditioning systems. The latter (packaged one half hp, 1,200 rpm motor and drive) is being sold to OEM customers for approximately $125 each, with exact prices depending on production volume and specific commercial arrangements (GE Motors, 1990). In Japan, PWM inverters are mass produced for small “mini-split” heat pump applications, reportedly at inverter manufacturing costs of $25/hp (at average rated motor power outputs of about 1.5 hp) (Greenberg, 1988 p. 7). Others place the direct material cost, based on large volume purchases, of the complete inverter for the Japanese, mini-split heat pumps at approximately $70/hp (GE Motors, 1990). With assembly costs, overhead, and profit margin added in, the full OEM pricing would be in the range of $100 to $125/hp.

It can be expected that the ultimate mass production OEM cost of a one-quarter horsepower motor rotor and stator plus a drive on a printed circuit board will cost well under $100. The cost of the three-phase motor rotor and stator subassemblies will be close to the cost of premium efficiency single-phase induction motors, in the range of $25, varying with output in the same fashion as induction motors. The OEM cost of the variable-speed drive (either SCIM or ECPM drive with PWM speed control) is expected to fall to $25 and $40, respectively, after several years of mass production.

The cost of the VSD could be offset, to some extent, by operating the motor and compressor at higher speeds, up to approximately 6,000 to 7,000 rpm, at its nominal capacity. Operating speeds of this magnitude are common for the variable-speed rotary compressors used in mini-split, room sized air conditioning systems, and should be compatible with smaller compressors used for refrigerator/freezer (R/F) units. This range of operating speed has also been demonstrated in R/F capacity reciprocating compressors, on a laboratory project basis (GE, 1990). These higher speeds are clearly feasible although issues related to the normal range of compressor design optimization and durability need to be addressed before commercial production.

The resulting reduction in compressor displacement and motor size would allow some reduction in the cost of these components, of approximately $5 to $10 at the OEM level. The variable-speed drive and motor replace the standard induction motor, whose OEM cost is about $15. The total offsetting cost reductions lie in the range of $20 - $25. The net increase in OEM component cost to the R/F manufacturer associated with the VSD/motors, in mass production, can be expected to be approximately $25 - $30.

In addition to motor and VSD costs, total applied costs will include the cost of the refrigerator temperature controller and a control algorithm. The temperature controller's function is to determine the required compressor speed and generate a speed control signal to the motor drive based on cabinet interior temperatures. These components replace the mechanical thermostats used in current refrigerators. For high-volume production, the costs are comparable with no net effect on the manufacturing cost or retail price of an R/F.

2.4 Variable-Speed Motor/Drive Costs—Fan and Small-Pump Motors

Appliance fans, furnace blowers, and small pumps have been typically powered by "sub-fractional" horsepower shaded-pole and permanent split capacitor (PSC) single-phase induction motors of relatively low efficiency. ECPMs of various forms offer more-efficient drive solutions when used as fixed-speed replacements for shaded-pole and PSC motors. Taking advantage of the variable-speed capability of ECPMs increases the system efficiency further. The efficiency and cost of shaded-pole, PSC, and ECPM refrigerator fan motors are presented in Table 2-3.

As may be seen in Table 2-3, the efficiency of small shaded-pole motors is very poor and the cost premium for improvement is substantial. Innovators have been seeking more cost-effective means to achieve higher efficiency in these small motors.

Table 2-3: Shaded Pole, PSC, and ECPM Refrigerator Fan Motor Efficiency and OEM Cost

Shaded Pole						PSC				ECPM			
Shaft Pwr (w)	Output Pwr (hp)	Input Pwr (w)	Eff (%)	OEM Cost ($)	Unit Cost ($/shaft-W)	Input Pwr (w)	Eff (%)	OEM Cost ($)	Unit Cost ($/shaft-W)	Input Pwr (w)	Eff (%)	OEM Cost ($)	Unit Cost ($/shaft-W)
6	0.01	40	15	7	$1.17	15	40	25	$4.17	9	71	35	$5.83
9	0.01	53	17	10	$1.11	21	43	28	$3.11	13	72	40	$4.44
15	0.02	75	20	15	$1.00	33	45	33	$2.20	21	73	42	$2.80
20	0.03	90	22	20	$1.00	42	48	35	$1.75	27	74	45	$2.25
25	0.03	110	23	25	$1.00	51	49	37	$1.48	33	76	48	$1.92
37	0.05	na	na	30	$0.81	70	53	40	$1.08	49	76	52	$1.41
50	0.07					90	56	43	$0.86	65	77	54	$1.08
125	0.17					202	62	51	$0.41	155	81	64	$0.51
249	0.33					370	67	57	$0.23	304	82	71	$0.29
373	0.50					530	70	60	$0.16	450	83	75	$0.20

Source: ADL, 1996

One such motor design employs the simple stator core and windings of the shaded pole unit but eliminates the shading ring. The laminated induction rotor with its die cast aluminum conductor cage replaced by a simple molded or extruded ferrite magnet sleeve and shaft assembly. This permanent magnet AC single-phase motor will self-start but the direction of rotation is dependent upon the initial position of the rotor. Some manufacturers of small pumps have successfully used such a motor with a pump that is effective for either direction of rotation. This mode of operation is limited however to sizes for which the ratio of motor torque to total motor plus load inertia is greater than a critical value. The viable size range is extended somewhat by employing rotor magnet material with a higher energy product such as bonded neodymium iron boron.

Others have developed means to reliably start a permanent magnet single phase AC motor in one direction for fans and other applications. For example, Advanced Motion Controls, Princeton WI, has developed a custom single chip electronic driver circuit to operate a permanent magnet single phase AC fan motor in an appliance manufactured by Whirlpool Corporation. The driver provides for reliable unidirectional starting as well as variable-speed operation. The advantage of this solution over existing ECPMs is a simpler and less costly motor construction.

Innovative three phase, brushless DC permanent magnet motor designs are also directed at reducing the cost of high-efficiency, variable-speed ECPMs for appliance and other high volume applications. For example, Wellington Electric of Torrington, Connecticut is developing and currently manufacturing permanent magnet, brushless, DC motors with stator windings automatically formed on a molded plastic frame. This “iron-less” construction avoids the cost of a laminated core. Core losses due to eddy current and hysteresis effects are also avoided but torque and power capabilities are compromised because winding flux linkage is not as strong as in conventional iron cored machines.

Moreover, absence of an iron core hampers the transport and dissipation of stator copper losses. Notwithstanding these potential limitations, motors of this type are finding commercial use for blowers and other applications. Wellington manufactures motors with no iron in conventional “radial flux” and “axial flux” configurations. The axial field design may be preferred because it uses only one low cost, ferrite magnet with multi-pole magnetization.

2.5 Current Research in Electric Motors for Commercial Applications

Various groups undertake research in motors for residential and commercial applications. Motor manufacturers do their own research, contract research to private firms, and support industry consortia and university research programs. Government also supports cooperative research efforts and individual programs, but to a lesser extent. Additionally, a great deal of research from other fields has applications to motor technology.

Research topics vary across research groups, but there are a few common drivers. First, induction motors are technically mature. Research expenditures therefore face diminishing returns. There are also added incentives for new technologies to capture market share from a mature technology. Second, substantial advances in other fields are expanding the potential applications for stepper motors and variable-speed control of induction motors. These include digital signal processing (DSP), power electronics, magnetic materials, and mathematical modeling. Applying these advances to motor technology has potentially high returns and is attracting a great deal of research activity.

Since induction motor technology is mature, most research focuses on reducing costs and increasing productivity rather than improving performance. Computer models to assist motor designers, new winding methods, and new steels are examples of typical research topics. Most motor manufacturers conduct this research internally, or contract out under proprietary arrangements.

Variable-speed control of induction motors is one area that continues to attract a great deal of research effort. Although also considered technically mature by virtue of their history in industrial process control, there is a large potential market in smaller industrial motors, and in fans, compressors, and appliance motors in the residential and commercial sectors. Furthermore, given the dominance of induction motors, there are retrofit opportunities. Since traditional methods of modulating induction motor speed or varying process rates can be extremely energy inefficient, end users have a financial incentive to switch to variable-speed drives. The attractive market draws private funding devoted to reducing costs and size and expanding applications. Universities and consortia are also researching ways to ameliorate the harmful effects of drive harmonics on power grids.

The same types of advances in power electronics and DSP are driving development of brushless DC motors such as ECPM. Advances in magnetic materials continue to support development of less costly, better performing, permanent magnet motors. Many DC motors are potentially less costly to manufacture than AC induction motors and have potentially higher electrical efficiencies because rotor slip is not present. The performance characteristics of a DC motor are determined as much by its controller as they are by its physical design. Research is underway in all circles to apply faster, more robust DSP controllers and new control strategies to motor applications traditionally served by induction motors, including the major residential and commercial applications in HVAC and refrigeration. DC motors are traditionally used in applications where position control, speed control, and small size are important. Energy efficiency, in these cases, is not considered. There are some challenges in optimizing motor design and control for applications where consumers value speed control and energy efficiency. The large potential market is drawing significant private research into DC motor modeling, design, and control to overcome these challenges. Because electronics continue to improve rapidly, DC motors have the potential to become a disruptive technology by promising both lower cost and better performance than induction motors. In fact, the market for DC motors may not be limited to applications now served by electric motors. The high torque, low speed capabilities of some advanced VSD motors have the potential to replace gearboxes and even internal combustion engines in some applications. The combination of decreasing risk and high return is attracting internal industry funding as well as support of consortia and university research.

Table 2-4: Involvement in Motor Research for Commercial and Residential Applications

Involvement level ● Significant ◉ Moderate ○ Small	Internal corporate research	Industry consortia	Industry sponsored university programs	Independent contract research	Government sponsored	Other industries
Induction motor speed control	●	○	●	○		●
Motor modeling		◉	◉	◉		
AC motor design	○			◉		
DC motor control	●		●			●
DC motor design	●		◉	◉		
Magnetic materials			○		○	◉
Steels			○		○	◉

2.5.1 Program Options

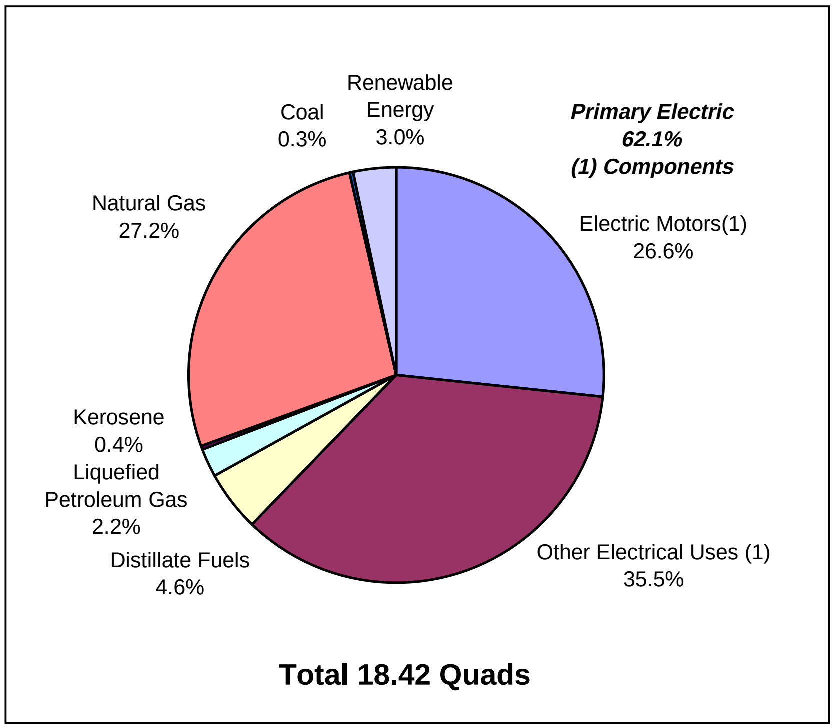
Markets trends, resulting largely from advances in control and power electronics, are opening the residential and commercial sectors toward DC motors and variable-speed controllers for induction motors. The large potential returns ensure ongoing private research in an effort to capture markets traditionally served by induction motors alone. Since one of the primary benefits of introducing these technologies into the residential and commercial sectors is energy savings, the outlook is good for reducing the energy consumption by fractional horsepower electric motors. Private research funding is high because of market incentives, and the resulting improvement in energy efficiency aligns itself with the Department's goals.

3 Motor Populations, Energy Usage, and Savings Potential in the Residential Sector

As shown in Figure 3-1, electric energy consumption in the residential sector accounts for over half of total sector, primary energy consumption. Electric motors consume about 43 percent of the total electric energy consumed in the residential sector. The major applications of electric motors in the residential sector and their energy use are discussed in this section.

Figure 3-1: 1995 Residential Energy Consumption by Fuel Type

Category	Energy Consumption	
	Quads	Percent
Primary Electric[1]	11.44	62.1%
Electric Motors[2]	*4.9*	*26.6%*
Other Electrical Uses[2]	*6.54*	*35.5%*
Distillate Fuels	0.89	4.6%
Liquefied Petroleum Gas	0.40	2.2%
Kerosene	0.07	0.4%
Natural Gas	4.98	27.2%
Coal	0.05	0.3%
Renewable Energy	0.59	3.0%
Total	**18.42**	**100%**



Sources: AEO 1998. Electric to primary energy conversion: 1 kWh = 11,005 Btu

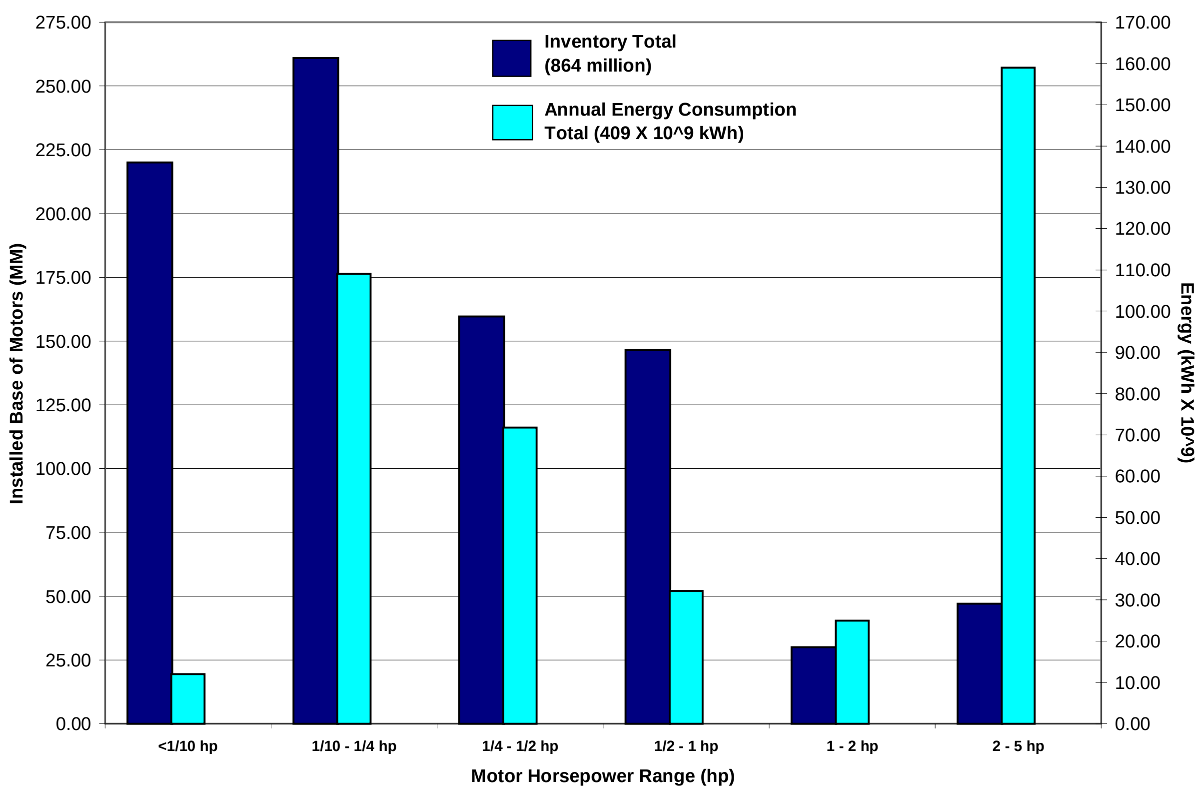
1 Includes generation, transmission, and distribution losses

2 Both components of the Primary Electric component

3.1 Residential-Sector Motor Population and Energy Usage

The population and energy consumption of residential electric motors in applications, other than those labeled “miscellaneous” or motors used with electric resistance heating devices, is depicted in Figure 3-2. The total nominal output of the installed base for these motors is approximately 608 million hp, and recent annual sales of new motors for residential sector applications total approximately 56 million hp. The vast majority of the motors are installed by OEMs in comfort conditioning products, major appliances, or small appliances. In the residential sector, these motors tend to be purpose built (e.g., rotor and stators installed in refrigerant compressors) as opposed to general purpose. The installed horsepower base of residential sector motors is divided between fractional horsepower motors (< 1 hp) and motors between 1 and 5 hp.

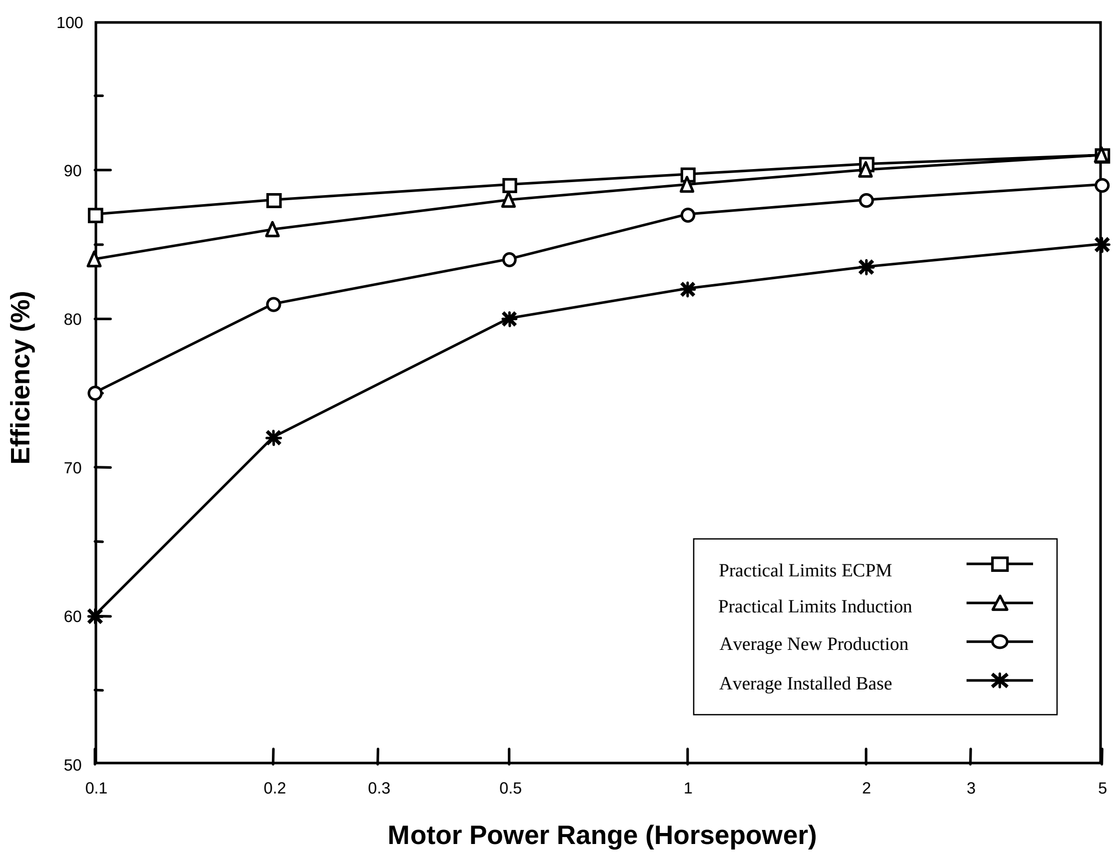
Figure 3-2: 1995 Residential Building Sector Motor Inventory and Motor Energy Consumption by Horsepower Rating for Major Applications



Sources: Tables 3-1

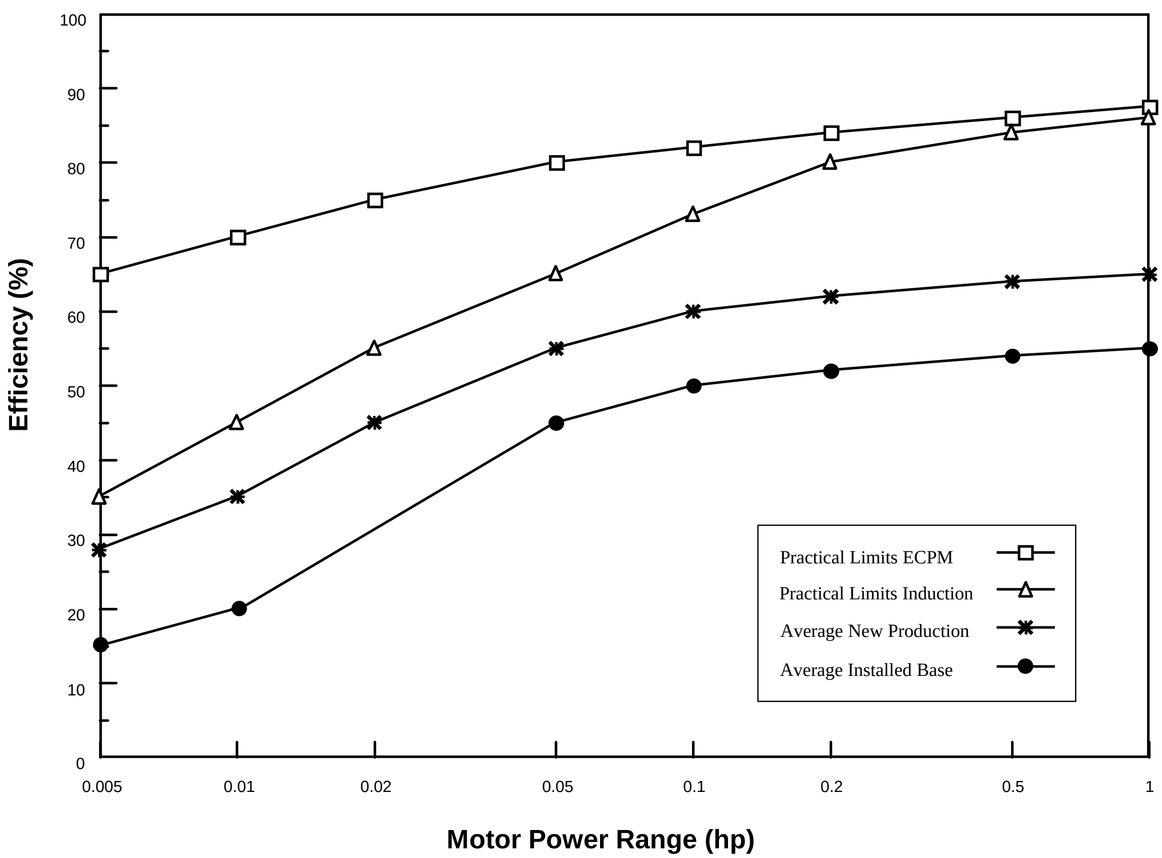
A broad understanding of motor efficiency distribution can be obtained by comparing the average installed base efficiency and average new production efficiency with the practical limits of both induction and ECPM motors to determine the unrealized efficiency gains. Figures 3-3 and 3-4 plot these efficiency levels. In the output ranges of residential size motors up to 5 hp, the average new production efficiency level is significantly higher than the average installed base. This is due to the strong influence of NAECA standards, which have been in effect since 1990, along with revised, tightened standard levels taking effect for many other appliance categories. New motors over 1/2 hp for residential applications are specified at efficiencies that lie within a few percentage points of the practical limits for induction motors. Higher-efficiency, permanent magnet, rotor motors (e.g., ECPM) are being used in increasing quantities. With two-thirds of the new motor sales resulting from replacement, and with typical residential appliance lifetimes of 10 to 15 years, the motor efficiency level of the installed base is increasing.

Figure 3-3: Comparison of Average Efficiency of Single Phase Two-Pole Hermetic Compressor Motors in the Installed Base and in New Equipment With Theoretical Limits (Electromechanical efficiency only)



Source: ADL Estimates

Figure 3-4: Comparison of the Efficiency of Other Single-Phase Motors



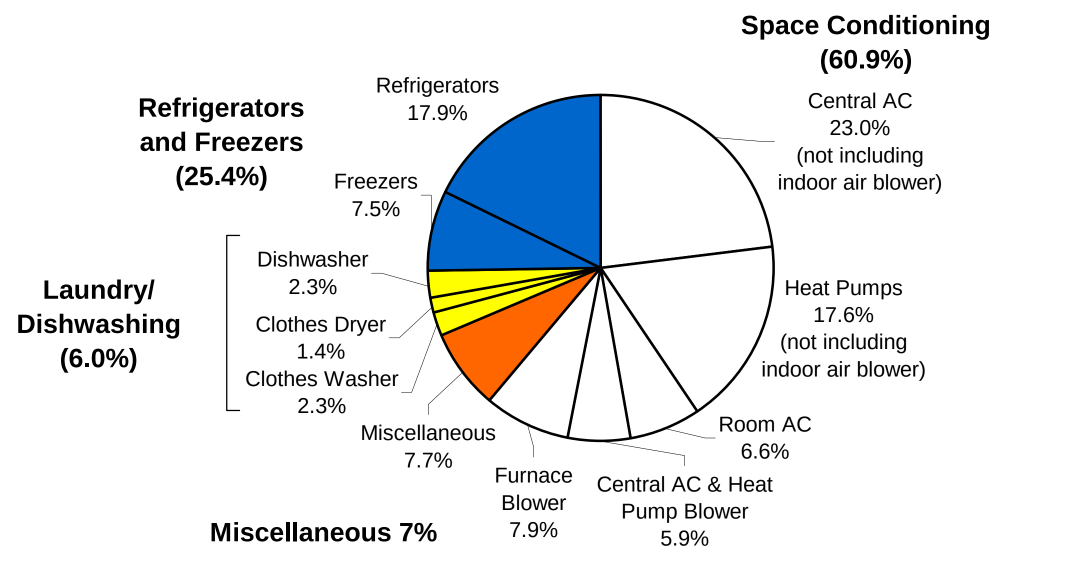
As indicated in Figure 3-1, motors used in residential applications account for slightly less than half of the overall residential electric energy consumption. Residential motor on-site electric energy consumption in 1995 was approximately 445 billion kWh; the corresponding primary energy consumption at the electric power plant being approximately 4.9 quads[1], or 26.6 percent of the total residential primary energy consumption. Motors are used for a variety of purposes in residential sector applications. Examples include space conditioning (refrigerant compressors in air conditioners and heat pumps, fans, and blowers), major appliances (refrigerators, freezers, clothes washers, dishwashers), small appliances (vacuum cleaners, floor polishers, food processors, hair dryers), power tools (drills, saws, sanders, etc.), and other applications (e.g., tape drives in audio and video cassette recorders, clocks, garage door openers, sump pumps, water well pumps). The energy consumption at the national level for a

[1]Conversion is: 11,005 Btu of power plant fuel consumption per site kWh of electric energy, based on DOE/EIA, AEO 1998 data for 1995.

particular motor application depends on the number in use, the power output, the efficiency, and the number of operating hours.

Figure 3-5 breaks down the residential motor energy consumption by application. The most significant applications are refrigerators, freezers, air conditioner and heat pump compressors and fans, and HVAC indoor air blowers (gas furnaces, central A/C, and heat pumps). These applications together account for more than 90 percent of total residential motor energy consumption. Percentages shown in the figure summarize the information found in Tables 3-1 through 3-3. This information is built from engineering estimates and the references noted. Each of these applications is covered in detail in the subsections that follow.

Figure 3-5: 1995 Residential-Sector Motor Energy Usage (Primary Energy: 4.9 Quads)

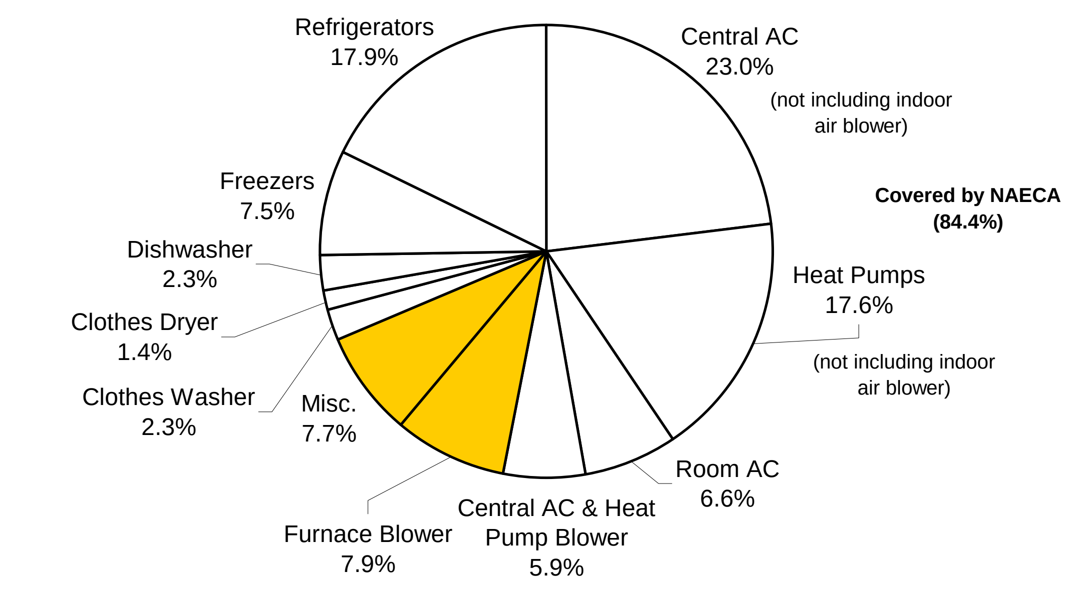


Source: Tables 3-1, 3-2, and 3-3
Conversion: 1kWh = 11,005 Btu

In the residential sector, motor efficiencies are strongly influenced by the minimum appliance, energy efficiency standards established under the National Appliance Energy Conservation Act (NAECA). Figure 3-6, based on similar residential motor, primary energy consumption data as Figure 3-5, is shaded to indicate whether the NAECA efficiency standards cover the particular motor application. More than 84 percent of the residential motor energy consumption occurs in appliances covered by NAECA, while the remaining 16 percent is in applications outside NAECA. NAECA standards have had a profound effect on the efficiencies of the motors used in most of these appliances.

The incremental cost of increasing motor efficiency is modest, so that increasing the motor efficiency has proven to be one of the most cost-effective ways to increase overall appliance efficiencies to meet the standards. As discussed below, as the NAECA standards took effect in the early 90s, dramatic increases occurred in motor efficiencies. In three of the NAECA covered appliances, standards have been a less powerful driver of motor efficiency. In clothes washers and dryers, the motor consumes only a small part of the total energy input compared to the heat input for water and air heating, respectively. The motor energy savings have little effect on the rated efficiency. The gas furnace test procedure does not include the indoor air blower power in the efficiency measurement. However, indoor air blowers integral to A/C and heat pump systems are covered in the standard.

Figure 3-6: 1995 Proportion of Residential-Sector Motor Energy Consumption in Applications Covered by NAECA



Source: Tables 3-1, 3-2, and 3-3
Conversion: 1kWh = 11,005 Btu

The original purchaser of the majority of the motors used in the residential sector is usually an OEM—the manufacturer of an appliance, an air conditioning or heating system, or other residential product. Large portions of these motors are supplied to the OEM as low-cost rotor and stator pairs integrated into the product, particularly in refrigerant compressors. These applications account for approximately two-thirds of the residential-sector motor energy consumption. The remaining OEM motors are commonly packaged in standard, purpose build configurations. Relatively few general-purpose motors are used in residential applications. Large power tools is one of the examples.

Table 3-1 summarizes the major residential-sector motor applications in terms of current inventory, power output range, efficiency, and energy consumption. Table 3-2 summarizes the annual unit sales and efficiency characteristics of the motors currently being used in these applications, and estimates the hypothetical annual consumption if the total installed base were operating at the current efficiency levels. Comparing Tables 3-1 and 3-2, it is readily apparent that motor efficiency levels have increased significantly, as discussed above. The motor applications summarized in Tables 3-1 and 3-2 account for about 95 percent of residential-sector motor energy and are the primary focus of this study. These electric motor applications are addressed, in detail, in later sections.

Table 3-1: Major Residential-Sector Electric Motor Applications—Installed Base

	Typical Motor - Current Installed Base				
Application	**Quantity (MM)**	**Horsepower Range**	**Efficiency Range (%)[1]**	**Operating Hr/year**	**Consumption 10^9 kWh/yr[2]**
R/F Compressor	117[3]	1/8 - 1/3	60 - 80	3,000	68
R/F Condenser Fan	117[3]	< 1/100	10 - 30	3,000	6
R/F Evaporator Fan	117[3]	< 1/100	10 - 30	3,000	6
Freezer Compressor	42[4]	1/8 - 1/3	60 - 80	3,000	33
Central A/C Compressor	36[3]	2 - 5	70 - 90	1,000	90
Central A/C Condenser Fan	36[3]	1/4 - 1/2	40 - 60	1,000	12
Heat Pump Compressor	11[3]	2 - 5	70 - 90	2,000 - 4,000	69
Heat Pump O.U. Fan	11[3]	1/4 - 1/2	40 - 60	2,000 - 4,000	9
Indoor Cooling Blower	47[5]	1/3 - 1	50 - 65	1,000	19
Indoor Heating Blower	67[5,6]	1/3 - 1	50 - 65	1,000 - 2,000	42
Room A/C Compressor	30[5]	1/2 - 2	70 - 90	500	25
Room A/C Fan/Blower	30[5]	1/8 - 1/2	50 - 60	500	4
Clothes Washer	79[3]	1/2	50 - 60	200[6]	10
Clothes Dryer Drum Rotation	82[4]	1/10	50	500	6
Dishwasher Pump	56[7]	1/2	60 - 70	300[6]	10
Miscellaneous (Table 3-3)	N/A	N/A	N/A	N/A	34
Total	**N/A**	**N/A**	**N/A**	**N/A**	**443**

1 Efficiency numbers used in this table may be somewhat lower than numbers cited for individual motors elsewhere in this document, to account for aging, oversizing and other losses in actual installations
2 Site electric energy - 90 billion kWh on-site is equivalent to about 1 quad of primary energy
3 DOE, 1998; data for 1997
4 USCB, 1995(a)
5 USCB, 1995(b)
6 Of indoor heating blowers installed, approximately 56 million are furnace blowers, the remainder heat pump blowers
7 ADL, 1998; data for 1997

Table 3-2: **Major Residential-Sector Electric Motor Applications—Current Production**

Application	Typical Motor - Current Production and Potential Consumption: Annual Units (MM)	Horsepower Range	Efficiency Range (%)	Operating Hr/year	Potential Consumption at Current Efficiency[1] 10^9 kWh/yr
R/F Compressor	10.3[2]	1/8 - 1/3	70 - 82	3,000	65
R/F Condenser Fan	9[2]	< 1/100	10 - 30	3,000	3
R/F Evaporator Fan	9[2]	< 1/100	10 - 65	3,000	1
Freezer Compressor	2.1[2]	1/8 - 1/3	70 - 82	3,000	32
Central A/C Compressor	5[3,4]	2 - 5	85 - 90	1,000	87
Central A/C Condenser Fan	5[3,4]	1/6 - 1/3	40 - 60	1,000	9
Heat Pump Compressor	-[4]	2 - 5	85 - 90	2000 - 4000	67
Heat Pump Outside Fan	-[4]	1/6 - 1/3	40 - 60	2000 - 4000	6
Indoor Cooling Blower	7[5,6]	1/3 - 1	50 - 80	1000	16
Indoor Heating Blower	-[5,6]	1/3 - 1	50 - 80	1000 - 2000	36
Room A/C Compressor	4.8	1/2 - 2	80 - 90	500	24
Room A/C Fan/Blower	4.8	1/8 - 1/3	50 - 70	500	4
Clothes Washer	7.6[2]	1/2	50 - 60	200	9
Clothes Dryer Drum Rotation	5.9[2]	1/10	50	500	6
Dishwasher Pump	5.1[2]	1/2	60 - 70	300	10
Miscellaneous (Table 3-3)	N/A	N/A	N/A	N/A	34
Total	**N/A**	**N/A**	**N/A**	**N/A**	**409**

1 Site electric energy, if the electric motors in the entire installed base noted in Table 3-1, operated at current new equipment, motor efficiency levels. These numbers generally correspond to the higher-efficiency induction motor options detailed in Tables 3-7 through 3-14
2 Appliance, April 1998
3 Appliance, April 1998; data for 1995
4 Sales figures for central A/C units include heat pumps
5 Appliance Web site, "www.appliance.com," estimate based on partial year data
6 Sales figures for heating and cooling blowers are combined under cooling blowers

Motors are used in many other residential products, but usually at a combination of low power, short operating hours, and/or small market penetration so that the energy consumption is relatively low. Table 3-3 shows a number of these miscellaneous residential motor applications which account for the estimated miscellaneous annual energy consumption representing 7.7 percent of residential energy use, or 0.38 quads of primary energy. This estimate, built up from estimates of individual end uses, agrees favorably with the 1998 DOE/LBL estimate of total (including non-motor) miscellaneous use of 0.68 quads.[1] The estimates of consumption for individual applications are in general agreement with figures from one or both of the

[1] LBNL, 1998

Table 3-3: Miscellaneous Residential-Sector Electric Motor Applications

Application	Installed Base (MM)	Annual Unit Sales (MM)	Typical Horsepower (hp)	Efficiency Range (%)	Typical Operating hr/yr	Consumption 10^9 kWh/yr
Vacuum Cleaner	99	15.7[1]	0.5 – 2	60	35	3
Dehumidifier	11[2]	0.8[1]	1/4	70	1,500[2]	11[4]
Attic Fan	9	1	1/3	40 – 60	< 200	< 1
Window Fan	55	1.9[1]	1/20 – 1/5	10 – 30	< 200	1
Hydronic Heating Pump	10	1	1/20 – 1/5	30 – 50	1,000 – 2,000	1
Pool Pump	6[3]				800[2]	4[4]
Evaporative Cooler Blower	4	0.3	1/4 - 1/2	50 – 60	500 – 2,000	3
Water Well Pump	14[3]	1	1/2 - 3	50 – 75	100[2]	1
Sump Pump			1/3	50 – 60	< 20	
Mixer, Food Processor, Blender	190	17.5[1]	1/50 – 1/10	20 – 30	< 20	< 1
Electric Can Opener	60	7.1[1]	1/50	10 – 20	< 10	< 1
Trash Compactor	4	0.1[1]	1/4	40 – 60	< 20	< 1
Garbage Disposal	48	4.8[1]	1/4	40 – 60	50	< 1
Garage Door Opener			1/3 – 1/2	50 – 60	50	
Large Power Tools			1 – 5	60 – 75	< 10	
Hand Held Power Tools			1/10 – 1	30 – 70	< 10	
Electric Lawn/Garden Tools			1/10 – 2	30 – 70	< 10	
Ceiling Fan	122[3]	14.8[1]				7[5]
Aquarium Pump	4[3]					
PC Fan (Residential)	41[3]		< 1/100		350[3]	< 1
Hot Tub/Spa Pump	4[3]					
Other Misc.						3
Total						**34**

1 Appliance, April 1998; 1997 data
2 ADL, 1998; 1997 data
3 DOE, 1998; data for 1997
4 ADL, 1998: converted from primary energy at 11,005 Btu/kWh
5 LBL, 1998; data for 1995

recent studies on miscellaneous use in the residential sector by Lawrence Berkeley National Laboratory and Arthur D. Little, Inc.[1] There appears to be a difference between the “Miscellaneous” motors value of 34 x 10^9 kWh (0.38 quads) as called out in the above table and the value of 15.9 x 10^9 kWh (0.18 quads) as called out in [ADL, 1998]. The differences are in the fact that [ADL, 1998] categorizes the small motors slightly

[1] LBL, 1998 and ADL, 1998

differently. The motors for the dehumidifier, window fans, evaporative cooler, and ceiling fans are categorized in the Space Cooling section of [ADL, 1998] while this report categorizes them in the miscellaneous motors category in Table 3-3. Also, the garage opener is grouped in the Electronics section of [ADL, 1998]. If the values for these 5 motor groups are added to the value for the "miscellaneous" motors category of [ADL, 1998], the new total then becomes 0.37 quads. This value and the 0.38 quads of this report are within approximately 3 percent of each other.

While many of the motors in miscellaneous uses are low in efficiency and not covered by EPAct or NAECA standards, the combination of short operating hours and low power levels results in a relatively low level of energy consumption. In addition to the residential motors itemized in Table 3-3, hundreds of millions of small motors, typically 1/1000 to 1/100 hp, are used in various applications. These applications include cooling electronic equipment (e.g., personal computers, microwave ovens), tape transports in VCRs and audio tape recorders, electric toothbrushes, electric carving knives and electric shavers. This diverse group of motor-powered appliances provides great convenience to people, while consuming negligible energy.

Table 3-4 summarizes residential motor applications in electric resistance heating devices such as space heaters and hair dryers. Because the motor losses add to the heat output of the electric resistance-heating element, there is no incentive to improve the efficiency of these motors. While there is no direct incentive to improve the efficiency of a blower used solely to distribute electric resistance heated air, most electric furnace installations also include central air conditioning. Therefore, the overall system efficiency does depend on the blower efficiency.

Table 3-4: Residential-Sector Electric Motors Used With Electric Resistance Heating Devices

Application	Installed Base (MM)	Annual Unit Sales (MM)	Typical Motor Horsepower
Indoor Electric Resistance Furnace Air Blower	11[1]	0.4[2]	1/3 – 3/4
Clothes Dryer Drum Rotation	60	4.5[3]	1/6
Convection Oven	5	0.5	1/6
Hair Dryers	~100	20.8[3]	1/100
Space Heaters (Fan-Forced)	25	3[3]	1/100

1 DOE, 1998
2 Appliance Web site, "www.appliance.com," estimate based on partial year data
3 Appliance, April 1998; data for 1997

3.2 Residential-Sector Motor Energy Savings Potential

From the preceding section, about 87 percent of the residential-sector motor energy consumption is concentrated in refrigeration and space conditioning applications. Therefore, the emphasis in analysis of energy savings potential is on these two applications.

In this section, the residential-sector energy savings potential and cost-effectiveness are evaluated for:

- Incrementally increasing the motor efficiency
- Application of adjustable-speed drives, where appropriate

The opportunities to save energy are evaluated in terms of their energy-saving potential and cost-effectiveness at current cost levels, as well as the potential to improve cost-effectiveness.

Figure 3-7 illustrates the overall potential for residential energy savings at various levels for the major applications that are analyzed in this chapter. When measures incorporating the use of both variable-speed drives and high-efficiency motors are considered, using the best option from summary tables 3-5 and 3-6, total savings potential is about 1.6 quadrillion Btus of primary energy. The energy savings potential for those residential measures with a payback of five years or less is about 594 trillion Btus. End uses for increased efficiency motors that are not included in this savings figure are room A/C fans/blowers, clothes dryer-drum rotation, dishwasher pumps, and miscellaneous applications. From Table 3-5 for increased efficiency motors, on a total use of $389x10^9$ kWh, there is a technical potential for savings of $45x10^9$ kWh. When subjected to economic evaluation, energy conservation options with payback periods less than five years yield potential savings of $23x10^9$ kWh. Other non-economic barriers may further reduce this figure. Use of variable-speed drives doubles this latter savings estimate.

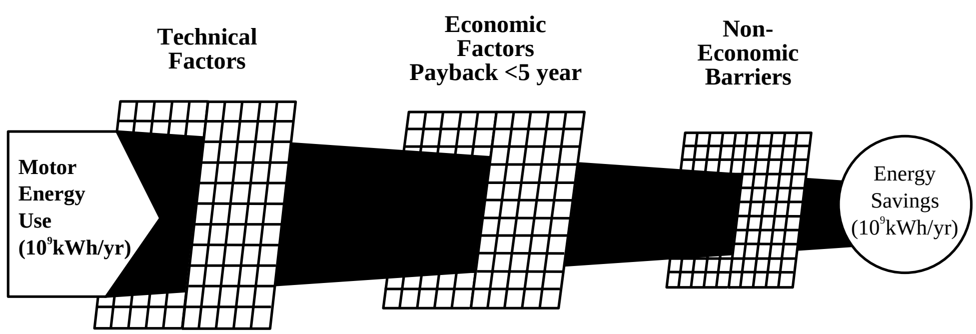
Tables 3-5 and 3-6 break out the savings for specific end uses. Table 3-5 summarizes the incremental efficiency gain over the efficiency of the installed base. This gain could be obtained by using the best practical (constant speed) motor technology and the estimated energy savings if the installed base were operating at the higher efficiencies. The numbers are generated from the figures and calculations presented in Tables 3-7 through 3-14. Incremental potentials add up to annual primary energy savings of about 0.5 quad (again, based on upgrading of the entire installed base from current motor efficiency levels to practical limits). Table 3-6 shows similar metrics for cases in which variable-speed technologies are implemented. Two factors should be noted:

- The use of several of these options, e.g., ECPM evaporator fans for refrigerators and freezers, is increasing rapidly under pressure of current and/or future NAECA standards. All of the end uses listed fall under NAECA standards, with the exception of indoor furnace blowers.

- Most of the options are at best only marginally cost-effective, with the exception of indoor blowers. Indoor furnace blowers stand out as an opportunity, as they are not presently covered by NAECA and have the potential for high-efficiency retrofit with low payback.

Figure 3-7: Energy-Saving Potential and Cost-Effectiveness of Increased-Efficiency Motors and VSDs in Major Residential Applications

Total Technical Savings Potential of about 146 x 10^9 kWh (1.6 quads)



Increased-Efficiency Motors	389	45	23	<23
Variable-Speed Drivers	350	126	46	<46
Best Option	393	146	54	<54

Source: Tables 3-5 and 3-6

Table 3-5: Potential Residential-Sector Energy Savings Through Increased Motor Efficiency

Application	Motor Energy 10^9 kWh/yr	Current Efficiency (%)	Practical Efficiency (%)	Energy Savings		Primary Energy Savings 10^{12} Btu	Typical Payback Years
				%	10^9 kWh		
R/F&F Compressor	101	80	82 - 84	4	4.0	44.5	14
Condenser Fan	6	15	65	77	4.6	50.8	6
Evaporator Fan	6	15	65	128	7.7	84.6	4
Central A/C & Heat Pump Compressor	159	87	90	3	5.3	58.3	16
Central A/C & Heat Pump O.U. Fan	21	50	70	29	6.1	66.0	6
Room A/C Compressor	25	87	90	3	0.8	9.2	13
Indoor A/C & Heating Blowers	61	60	80	25	15.3	168.4	3
Clothes Washer Motor	10	65	75	13	1.3	14.7	10
Total	**389**	**N/A**	**N/A**	**N/A**	**45**	**497**	**N/A**

Basis: Upgrade installed motor base to maximum, practical efficiencies level
Source: Tables 3-7 through 3-14
Assumptions: An electric rate of $0.08/kWh is used; evaporator fan savings include reduction in refrigeration (compressor) load; primary energy savings are calculated at the 1995 value of 11,005 Btuh/kWh

Table 3-6 summarizes the efficiency gains and primary energy savings that could be attained by using variable-speed motor technology. The tables represent the information presented in Tables 3-7 through 3-14 and use the same baseline data and analysis approach as for the data in Table 3-5 for increased efficiency motors. Table 3-6 shows that significant savings, adding up to nearly 1.4 quads, could be attained. However, the incremental cost is significant, and the payback period for average applications is much greater than five years, with the exception of indoor blower motors. The following subsections discuss the specific end uses, energy savings opportunities, and the assumptions behind these energy savings estimates.

Table 3-6: Potential Residential-Sector Energy Savings Through Variable-Speed Motors

Application	Motor Energy 10^9 kWh/yr	Current Efficiency %	Practical Efficiency %	Energy Savings		Primary Energy Savings 10^{12} Btu	Typical Payback Years
				%	10^9 kWh		
R/F&Freezer Compressor	101	80	88	20	20.2	222	8
Central A/C & Heat Pump Compressor[1]	159	87	90	35	55.7	612	15 - 25
Room A/C Compressor	25	87	90	10	2.5	28	20+
Room A/C Fan/Blower	4	60	75	50	2.0	22	10
Indoor Heating & A/C Blowers	61	60	80	75	45.9	504	2 - 3
Total	**350**	**N/A**	**N/A**	**N/A**	**126**	**1388**	**N/A**

1 With a 2-speed induction motor, somewhat higher energy savings are possible with continuously variable speed, but the payback period is longer (see Tables 3-9 and 3-10).
Basis: Replace single speed motor with efficient variable-speed drive and motor.
Source: Tables 3-7 through 3-14
Assumptions: An electric rate of $0.08/kWh is used. Evaporator fan savings include reduction in refrigeration (compressor) load. Primary energy savings are calculated at the 1995 value of 11,005 Btuh/kWh. Savings include process energy savings due to more efficient part load operation.

Note that there are many design options for improving the system efficiency besides improving the motor efficiency or using variable-speed drives for efficient part load operation. Obvious examples include increased insulation, larger heat exchangers, adaptive defrost, etc. An inherent advantage of the NAECA efficiency standard setting process is that once a standard level is set, manufacturers are free to develop the most cost-effective design to meet the standard. Thus, motor efficiency increases are only part of the potential for efficiency improvement in these types of appliances. This observation is consistent with other published studies [ACEEE, 1995] of the potential for reduced energy consumption by motor driven equipment. Incremental, motor efficiency improvements generally account for only 10 to 20 percent of the estimated potential energy savings. The majority of these savings come from equipment, product, or process redesign. The use of adjustable-speed drives, which often requires a redesign for the driven process, typically involves a much larger scope of activity than incrementally increasing the motor efficiency.

3.2.1 Domestic Refrigerators and Freezers

Conventional domestic refrigerators and freezers can include up to three motors. The largest (typically 1/8 to 1/3 hp) motor drives the refrigerant compressor, which is needed in all refrigerators and freezers. The other two, much smaller motors (with shaft power outputs of a few watts) drive fans and force air over the condenser and evaporator. The majority of frost-free refrigerators and freezers use a forced draft evaporator and condenser. However, many manual defrost refrigerator/freezers, chest freezers and small, under-counter type refrigerators use a natural convection (sometimes referred to as a “static”) condenser and/or evaporator, and, therefore do not use the additional fan motors.

From Table 3-6, variable-speed ECPMs used to power refrigerators and freezer compressors combined with ECPM driven condenser and evaporator fans have the potential to reduce primary energy consumption by 222 x 10^{12} BTUs annually. At current retail costs, the combined measures have a payback of eight years. When only the fans are evaluated, the payback is reduced to five years.

NAECA will increase the likelihood that refrigerator manufacturers will rely on efficient motor technologies to meet the more stringent requirements. A great deal of research and development expertise has been expended in the area of high-efficiency evaporator fan motors. The emphasis is not only on radical departures from conventional motor technologies however. Careful examination of the motor system, including the fan blade has increased efficiency without adding significantly to cost. Cost-effective opportunities remain for system improvement in meeting standards. As the production increases for ECPM fan motors, the cost premiums can be expected to fall. In 2001, allowable refrigerator and freezer energy consumption will be reduced by an average of about 25 percent from current levels. This is likely to result in some use of variable-speed compressors, with the resulting sales volume also leading to gradual reductions in cost.

Table 3-7 estimates the potential efficiency improvements and energy savings that could be attained compared to the installed base through incrementally higher motor efficiencies or variable-speed, based on the discussion that follows below. Table 3-8 estimates the payback for each of the options in Table 3-7, for the average application and average residential electric rates.

Table 3-7: Potential for Energy Savings Through Increased Efficiency and Variable-Speed Refrigerator/Freezer Motors (Base Site Motor Energy[1] = 113 x 10^9 kWh/yr)

Motor (Base Energy, 10^9 kWh/yr)	Current Motor Efficiency (%)	Efficient Motor Option	Possible Efficiency (%)	Estimated Annual Energy Savings[2]		
				On-site		Primary 10^{12} Btu
				Percent (%)	10^9 kWh	
Compressor (101)	80	Higher-Efficiency Induction Motor	82 - 84	4	4.0	45
		Fixed-Speed ECPM	88	9	9.2	101
		Variable-Speed ECPM[3]	88	20	20.2	222
Condenser Fan (6)	15	High-Efficiency PSC Motor	30	50	3.0	33
		ECPM	65	77	4.6	51
Evaporator Fan (6)	15	Higher-Efficiency PSC Motor	30	83[4]	5.0	55
		ECPM	65	128[4]	7.7	85

1 Base Site Motor Energy -- the estimated annual motor site electric energy consumption for this application, based on the efficiency of all motors in the installed base (Table 3-1).
2 Energy savings based on application of efficient motor option to the entire installed base, compared to base energy
3 In conjunction with a variable-speed ECPM evaporator fan
4 Energy savings include reduced compressor energy due to reduced refrigeration load @1.5 COP

Table 3-8: Cost-Effectiveness of Efficient Motor Options for Refrigerator/Freezers—Estimated Payback for Average User at an Average Electricity Rate ($0.08/kWh)

Motor	Average UEC[1] kWh/yr	Efficient Motor Option	Energy Savings		Additional Retail Cost, $	Simple Payback, Years
			Percent (%)	$/yr		
Compressor	570	Higher-Efficiency Induction Motor	4	1.80	25	14
		Constant-Speed ECPM	9	4.10	60	15
		Variable-Speed ECPM	20	9.10[2]	75	8
Condenser Fan	50	Higher-Efficiency PSC Motor	50	2.00	10	5
		ECPM	77	3.10	20	6
Evaporator Fan	50	Higher-Efficiency PSC	83	3.30	10	3
		ECPM	128	5.10	20	4

1 Unit Energy Consumption per year, based on Table 3-1 and engineering estimates
2 Used with a variable-speed ECPM evaporator fan, included in the "additional retail cost"

3.2.1.1 Impact of NAECA Standards

Efficiency standards for refrigerators and freezers under NAECA went into effect in 1990. The 1990 standard was replaced by a more stringent, revised standard in 1993 that, on the average, lowered the allowable energy consumption of refrigerator/freezers by approximately 25 percent. A further revision of the standard will take effect in 2001 and is projected to reduce allowable energy consumption by a further 25 percent. These standards are very stringent. In the late 1970s, the average 18 cubic foot top-mount refrigerator/freezer consumed approximately 2,000 kWh/year under standard DOE test conditions. The allowable energy consumption of this average 18 cubic foot top-mount unit under the current standard (1993) is approximately 670 kWh/year, about one-third of previous levels and approximately equivalent to a continuously powered 75W light bulb. This reduction in energy consumption was achieved through various design changes. The reduction of energy consumption to the 1,000 kWh/year level allowed in the 1990 standard, was largely achieved through cabinet design changes, especially the substitution of polyurethane foam insulation for fiberglass. Further reductions of energy consumption to the 1993 standard level have relied heavily on motor efficiency improvements.

3.2.1.2 Compressor Motor

In domestic refrigerators and freezers, a 115 VAC, single-phase, two-pole induction motor always drives the refrigerant compressor. The installed base includes several basic variants (e.g., RSIR, CSIR, and RSCR) but as a result of the NAECA standards, in new compressors, the vast majority of the compressor motors are one of the higher efficiency capacitor run types. In anticipation of the more stringent 2001 standards, manufacturers are already beginning to assess the higher-efficiency, higher-cost ECPM motor, configured either as a high-efficiency constant-speed motor, or as a variable-speed motor.

Americold has worked with GE Motors to develop an ECPM motor driven compressor, in both single speed and variable-speed versions. The single speed compressor has an EER approaching 6.0 Btu/Wh, compared to 5.6 Btu/Wh in an otherwise equivalent, induction motor driven high-efficiency model, with the difference in efficiency being attributable solely to the motor efficiency. Variable-speed models are capable of running at speeds down to half the design speed.

The use of a variable-speed ECPM driven compressor in combination with variable-speed ECPM evaporator and condenser fan motors was examined in [EPA, 1993a]. Energy savings of approximately 25 percent were estimated. An incremental retail price of $75 was assumed in the present analysis. This somewhat optimistic figure is based on incremental OEM cost of $30 for the compressor, $15 for the ECPM fans, marked up to $75 at retail. The resulting payback period is about eight years, even under this optimistic scenario of the retail price impact. Additional benefits of variable speed include very quiet, steady-state operation and rapid pulldown when warm food is placed into the cabinet.

3.2.1.3 Evaporator Fan Motor

Increases in evaporator fan motor efficiency result in a “double” increase in refrigerator efficiency, because the fan and motor are located within the refrigerated cabinet and the electric energy input adds to the refrigeration load. Thus, not only does increasing the efficiency of this motor directly reduce the fan power, but compressor power is reduced as well, by virtue of the reduced refrigeration load. At current typical refrigeration system COP levels of approximately 1.5, compressor energy is reduced by an additional two-thirds of any reduction in the evaporator fan energy use.

Until recently, shaded pole motors, with efficiencies between 10 and 15 percent and power draw of about 15, were commonly used. The 1993 NAECA standard has resulted in widespread use of higher (20 to 30 percent) efficiency PSC motors, reducing the input power below 10W. The highest efficiency evaporator fan motor is an ECPM motor, whose efficiency is typically 65 percent and typical power input is 6W. The OEM cost premiums over shaded pole for PSC and ECPM motors are approximately $5 and $10, respectively (typical OEM prices for shaded pole, PSC, and ECPM fan motors are $5, $10, and $15, respectively). Despite the significant cost premium, ECPM evaporator fan motors are under serious consideration as the more stringent 2001 NAECA standards approach closer.

3.2.1.4 Condenser Fan Motor

Condenser fan motors in the installed base are generally low cost, low efficiency shaded pole induction motors, with efficiencies of approximately 10 percent. Typical power consumption is approximately 15W. Again, under the pressure of NAECA standards, higher-efficiency (20 to 30 percent) PSC motors are being used, reducing the power consumption to below 10W. ECPM fan motors that are more efficient could be used as well, but the effective savings are only half that obtained with evaporator fan motors even with the additional effect that it has on the refrigeration load. From the data in Table 3-8, the typical payback period for the investment in an ECPM motor (over a PSC motor) in the condenser fan is 10 years.

3.2.2 Central Air Conditioners and Heat Pumps

Central air conditioners and heat pumps generally include two major sections:

- An outdoor unit containing the compressor, the condenser (or heat pump outdoor coil, which operates as the evaporator in heating mode) and the condenser fan

- An indoor unit containing the evaporator (or heat pump indoor coil, which operates as the condenser in heating mode) and the indoor air blower

The majority of central air conditioners are split systems with only 10 percent being single package units. Both sections of the single packaged unit are located outdoors with ducts running to and from the indoor conditioned space. The outdoor fan is operating when there is a requirement for heating or cooling within the conditioned space. The indoor blower distributes cooled or heated air throughout the interior depending on the need. The heat sources include a heat pump cycle, electric resistance heat, a gas or oil furnace, or a hot water heating coil. In addition, a significant percentage of warm air furnaces are installed without central air conditioning. Because the indoor blowers and their drive motors are similar regardless of the exact combination of heating or cooling devices, they are both discussed separately from the systems they serve in the next section.

The technically feasible primary energy savings from efficient motors and VSDs for central system compressors is over 600 x 10^{12} BTU annually (Table 3-6). The majority of these savings are obtained with a variable capacity compressor (two-speed, dual compressor, or continuously variable speed) combined with a variable-speed indoor blower motor. At current costs for this option, the payback exceeds 15 years. Of the measures identified, the use of higher-efficiency PSC motors in the indoor fan offers the best payback at three years.

In general, other incremental increases in motor efficiency beyond the levels in common use will not result in significant energy savings nor be particularly cost-effective, with payback periods typically greater than 10 years. The same applies to substituting the higher-efficiency technology as part of the design of new equipment. Only the incremental cost of the higher-efficiency motor technology, more than the cost of commonly used technology, is considered in the payback calculation.

Finally, there is no real opportunity to cost-effectively retrofit more efficient motors into existing residential equipment. Many motors are closely integrated with the equipment, particularly hermetic compressor motors within sealed refrigeration systems. Even for motors that can indeed be replaced, total installed costs are prohibitive compared to the value of the energy savings. A variable-speed indoor blower motor, in another example, cannot be added to a fixed capacity system.

Table 3-9 summarizes the potential energy savings in air conditioning/heat pump compressors and outdoor unit fans, using incrementally higher-efficiency motors or variable-speed drives. Table 3-10 estimates the cost-effectiveness of these options. The tables are followed by a discussion of the technologies.

Table 3-9: Potential for Energy Savings Through Increased-Efficiency Central Air Conditioner and Heat Pump Motors (Base Site Motor Energy[1] = 180 x 10^9 kWh/yr, not including the indoor air blower)

Motor (Base Energy, 10^9 kWh/yr)	Current Motor Efficiency Percent	Efficient Motor Option	Possible Efficiency (%)	Estimated Annual Energy Savings[2]		
				On-site		Primary 10^{12} Btu
				Percent (%)	10^9 kWh	
Compressor (159)	87	Higher-Efficiency Induction Motor	90	3	5.3	58
		2-Speed Motor	85	30[3]	47.7	525
		Variable-Speed ECPM	90	35[3]	55.7	612
O.U. Fan (21)	50	High-Efficiency PSC Motor	70	29	6.1	66
		ECPM	80	38	7.9	87

1 Base Site Motor Energy -- the estimated annual motor site electric energy consumption for this application, based on the efficiency of all motors in the installed base (Table 3-1).
2 Energy savings based on application of efficient motor option to the entire installed base, compared to base energy
3 Used in conjunction with a variable-speed indoor blower motor. Includes savings due to variable capacity operation.

Table 3-10: Cost-Effectiveness of Efficient Motor Options for Central Air Conditioners and Heat Pumps—Estimated Payback for Average User at Average Electricity Rate (0.08/kWh)

Motor	Average UEC[1] kWh/yr	Efficient Motor Option	Energy Savings		Additional Retail Cost, $	Simple Payback, Years
			Percent (%)	$/yr		
Compressor (159)	2,000	Higher-Efficiency Induction Motor	3	4.80	60	12
		2-Speed Motor	30[2]	48	500 – 1,000	10 - 20
		Variable-Speed ECPM	35[2]	56	1,000 – 1,500	15 - 25
O.U. Fan (21)	150	Higher-Efficiency PSC Motor	29	3.50	20	6
		ECPM	38	4.60	50	11

1 Note that UEC (ADL estimate) varies with climate and other site-specific variables. In areas with a long cooling season, larger savings and shorter payback periods result.
2 Used with a variable-speed indoor blower motor, included in the "additional retail cost".

3.2.2.1 Single-Speed Compressor Motor

Welded hermetic compressors are used in virtually all residential air conditioners and heat pumps. The efficiency level of compressors has been steadily increasing since the 1970s. In 1975, a typical hermetic reciprocating compressor would have an energy efficiency ratio (EER) of 8.5 Btu/W - hr (compared to an isentropic compressor driven by a 100 percent efficient motor, which could have an EER of 16.5). During the early 1980s, reciprocating compressors with EER levels of 10.0, were introduced and since

1990, scroll compressors and high-efficiency reciprocating compressors having with EER values between 11.0 and 11.5 have been mass-produced.

With the exception of a small number of two-speed and variable-speed compressors, all compressors are driven by two-pole, CSCR single-phase induction motors. Most compressor models are also available with 3-phase motors for small commercial air conditioning applications.

The aforementioned increase in the overall compressor EER has been achieved through a combination of improved compressor design and increased motor efficiency. During the mid-70s, compressors motor efficiencies were somewhat less than 80 percent; in current compressors, motor efficiencies range from 87 to 90 percent, approaching within two to three percentage points of practical limits.

NAECA minimum efficiency standards have driven the latest increases in compressor efficiency levels (from 10.5 to 11.5) and compressor motor efficiency levels. Relatively little increase in compressor efficiency levels can be expected, given the relatively close further practical limits of both the compressor and motor. For example, an 80 percent efficient compressor driven by a 90 percent efficient motor would have an EER of 11.8, only slightly higher than current products. Increases beyond these levels are exceedingly difficult to attain at the 2 to 5 hp residential size. Thus, relatively little potential for efficiency improvement remains.

As discussed below, variable-speed configurations can save significant amounts of energy.

3.2.2.2 Variable-Speed Compressor Motor

The capacity of an air conditioner is generally specified based on the anticipated maximum cooling load of the house, usually established by the design ambient temperature and maximum mid-day solar heat gain. The ability to meet the cooling load, under these conditions, is important to consumer satisfaction with the product. However, a large majority of the operating hours occurs under much milder conditions, requiring only a fraction of the cooling capacity of the air conditioner. In a typical central air conditioner having a single speed compressor, the unit cycles on and off, in response to a thermostat, to maintain the conditioned space at the desired set temperature. Under part load conditions, continuous operation at efficiently modulated capacities is considerably more efficient than on/off cycling at full capacity, due to several factors:

- When operating continuously at part load, the heat exchangers are better utilized, resulting in a lower condensing temperature and a higher evaporating temperature, increasing the compressor COP significantly.

- Losses associated with on/off cycling can amount to 5 percent or more of the total losses and are eliminated with continuous operation.

- At reduced capacity, the indoor air flow rate can be reduced. When this is done with a variable-speed blower, the speed cubed power law results in significant energy savings at 2/3 capacity and below.

A similar reasoning applies to the operation of a heat pump in heating mode. There are two basic options for implementing capacity modulation:

- A continuously-variable-speed, motor-driven compressor with the ECPM motor– the most efficient option; the application of a variable-speed compressor to a system along with an ECPM indoor blower results in an efficiency increase. This increase can be expressed by improving the SEER value about 50 percent over an otherwise identical single-speed compressor system (e.g., from 10 Btu/Wh to 15 Btu/Wh).

- A two-speed motor, which results in a 30 to 40 percent efficiency increase (e.g., SEER increases from 10.5 Btu/Wh to 14 Btu/Wh)

- Other non-motor-based discrete capacity steps, such as dual compressors (used in the York "Stellar Ultra" product line) or cylinder unloading (as in the Bristol "Digital Inertia" compressor)

As indicated in Table 3-10, the most cost-effective option is the two-speed compressor, but none of the options returns a particularly short payback to the average user.

3.2.2.3 Condenser Fan Motor

The condenser fan motor power consumption is typically about 5 percent of the total air conditioner power consumption. A more efficient motor would result in some energy savings, with the savings from a more efficient PSC motor resulting in an approximate five-year payback.

3.2.3 Indoor Air Blowers in Forced Draft Heating and Air Conditioning Systems

As discussed in the preceding subsection, indoor blowers are used to force cooled or heated air through ductwork, for central air conditioning and for heating from a variety of sources. The indoor blower imparts sufficient static pressure to overcome the pressure losses in the system. These losses consist of the pressure losses through the furnace core, the air filter, the evaporator coil, the supply air ducts and diffusers, and the return air path (separate ductwork or through the conditioned space). Basically, it is a system of fixed flow resistances, with the individual pressure drops being proportional to the square of the flow rate and the air moving power being proportional to the cube of the flow rate.

Conventional blower motors are typically multiple speed-shaded pole or PSC induction motors. Typically, one of the available speed levels is selected at the time of installation to match the blower output with the flow resistances in the space conditioning equipment and the duct system. The typical efficiency of this type of motor lies between 50 and 60 percent.

Table 3-11: Potential for Energy Savings Through Increased-Efficiency Indoor Blower Motors (Base Site Motor Energy[1] = 61 x 10^9 kWh/yr)

Motor (Base Energy, 10^9 kWh/yr)	Current Motor Efficiency %	Efficient Motor Option	Possible Efficiency (%)	Estimated Annual Energy Savings[2]		
				On-site		Primary 10^{12} Btu
				Percent (%)	10^9 kWh	
Central A/C Blower (15)	60	High-Eff PSC	70	14	2.1	24
		ECPM	80	25	3.8	41
		Var-Speed ECPM	80	75	11.3	124
Heat Pump Blower (11)	60	High-Eff PSC	70	14	1.6	17
		ECPM	80	25	2.8	30
		Var-Speed ECPM	80	75	8.3	91
Furnace Blower (35)	60	High-Eff PSC	70	14	5.0	55
		ECPM	80	25	8.8	96
		Var-Speed ECPM	80	75	26.3	289

1 Base Site Motor Energy -- the estimated annual motor site electric energy consumption for this application, based on the efficiency of all motors in the installed base (Table 3-1).

2 Energy savings based on application of efficient motor option to the entire installed base, compared to base energy

Table 3-12: Cost-Effectiveness of Efficient Motor Options for Indoor Blowers—Estimated Payback for Average User at Average Electricity Rate (0.08/kWh)

Motor	Average UEC kWh/yr	Efficient Motor Option	Energy Savings		Additional Retail Cost, $	Simple Payback, Years
			Percent	$/yr		
Central A/C Blower	400	Higher Eff PSC	14	4.50	15	3
		ECPM	25	8.00	40	5
		Var Speed ECPM	75	24.00	75[1]	3
Heat Pump Blower	1,000	Higher Eff PSC	14	11.20	15	1
		ECPM	25	20.00	40	2
		Var Speed ECPM	75	60.00	75[1]	1
Furnace Blower	600	Higher Eff PSC	14	6.70	15	2
		ECPM	25	12.00	40	3
		Var Speed ECPM	75	36.00	175[2]	5
Central A/C and Furnace Blower	1,000	Higher Eff PSC	14	11.20	15	1
		ECPM	25	20.00	40	2
		Var Speed ECPM	75	60.00	175[2]	2

1 Cost of variable-speed blower only
2 Includes incremental cost of $100 for capacity modulation in the furnace

3.2.3.1 Variable-Speed Motor/Blower

Electronically commutated permanent magnet rotor brushless DC motors are now commercially available and being increasingly used (in 5 to 10 percent of all new residential indoor air blower applications). Two basic operating modes are used. The most common mode is a constant flow set-up, where the motor controller is programmed, based on the blower performance characteristics, to provide a preset air flow rate. The rate is typically 400 CFM per ton of air conditioning capacity, regardless of the system static pressure losses. Energy is saved by virtue of the high efficiency (80 to 82 percent motor/electronic drive system efficiency) at the design speed and by providing the optimum airflow rate. This operating mode is used with air conditioners and heat pumps having a constant speed compressor.

Operation in variable speed results in much larger blower-motor energy savings. In this mode, the blower speed and air flow rate are varied in proportion to the cooling or heating load, in conjunction with modulated outputs of the air conditioner, heat pump, gas furnace, or other heat source. Figure 3-8 illustrates the potential blower motor power savings. The curve on the right is the theoretical speed, cubed fan power law for a typical residential system of fixed flow resistances. The curve on the left shows the actual flow-power characteristics of the ECPM/blower, accounting for the decrease of ECPM/electronic drive system efficiency with speed. The actual ECPM/blower realizes the majority of the potential for power reduction by reducing the airflow to match load, thus disproportionately reducing the power consumption.

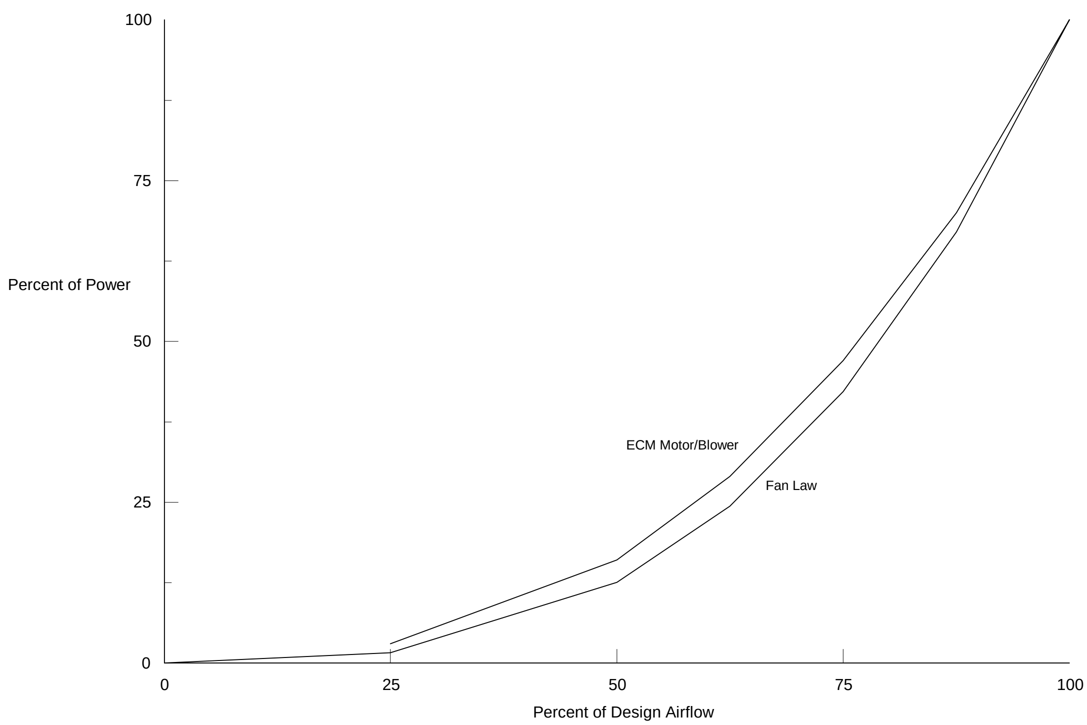
In air conditioning mode, reduced blower power consumption also reduces the cooling load by the same amount, because blower power dissipation contributes an internal load to the house. At a typical, seasonal average compressor COP of 4.0, compressor power savings are 25 percent of any reduction in blower motor power input. However, in heating mode, the opposite occurs. Less blower energy dissipation requires additional heat input. On a primary energy basis, the energy increase is 25 - 35 percent of the saved blower motor energy. Overall, the two effects tend to negate each other. Thus, no net effect on the energy consumption of other system components is assumed in Tables 3-11 and 3-12.

The energy saving potential is significant compared to operating in on/off mode. For example, at 50 percent output, the actual electric power to the blower is 10 percent of the power input to a conventional blower motor. However, the operating time is approximately double. Therefore, the net energy consumption over time is 20 percent of the on/off mode energy consumption of a conventional blower motor.

As indicated in Table 3-12, a variable-speed ECPM blower is generally cost-effective, considering air moving equipment cost and air moving energy cost savings. However, a modulated heating or cooling source generally must be used in conjunction with the variable capacity blower, so the energy savings and cost-effectiveness are more properly viewed in the context of a complete variable capacity system. In section 3.2.2, the contribution of the ECPM blower to both the cost and performance of variable capacity air conditioning and heat pump systems is included in the estimated energy savings and payback period.

In the case of a warm air gas or oil furnace (the third case in Tables 3-11 and 3-12), the estimated incremental cost of a modulated firing rate is included in the additional retail cost. In this instance, even when the cost of modulated firing is included, the variable-speed blower is still cost-effective.

Figure 3-8: Variable-Speed Motor/Blower Power Consumption Characteristics



3.2.4 Room Air Conditioners

Room air conditioners (RAC), often called window air conditioners, consume about 1/6 of the energy consumed by central air conditioners and heat pumps in the residential sector. The lower energy consumption is the result of lower unit capacities and shorter duty cycles. RACs also have comparable annual unit sales to central systems as well as shorter average product lifetimes. They are arranged so that one double-ended motor drives both the condenser fan and the indoor air blower. Therefore, room air conditioners have two motors—the compressor motor and the double-ended fan/blower motor.

Significant energy savings can be obtained through variable capacity design of residential central air conditioners and heat pumps. Through the use of the DOE energy efficiency test procedure for residential central air conditioners and heat pumps [CFR 430, Subt. B, Appendix M], a reasonable degree of consensus can be obtained concerning the energy savings. The DOE test procedure includes methods for measuring the impact of several variable capacity options including multiple compressors, multiple speed compressors, and continuously variable-speed compressors. These procedures were developed with significant industry input.

In contrast, there is no consensus test procedure for measuring energy savings due to variable capacity design features of a room air conditioner. In DOE test procedure (CFR 430, Supt. B, Appendix F), the air conditioner is tested under a single set of standard conditions, at full capacity. In actual use, the homeowner will often want to operate at less than full capacity. This is done more efficiently with a variable-speed compressor and an ECPM fan/blower motor than with the typical arrangement of compressor on/off cycling and multi-speed induction fan motors. The validity of a variable capacity test procedure for room air conditioners, which could be used to calculate real world energy savings, is debatable because many variables beyond the outdoor temperature enter into the occupants' selection of the capacity.

Nevertheless, some level of energy savings could be expected with an efficient variable-speed fan motor, a variable-speed compressor, or a combination of the two, because:

- The typical RAC has a two- or three-speed fan motor, which is particularly inefficient at lower speeds, while an ECPM motor would capture most of the savings associated with the speed cubed fan law.

- At reduced fan speeds, a variable-speed compressor would also operate at a reduced speed, raising the evaporating and lowering the condensing temperatures, and improving the COP.

3.2.4.1 Compressor Motor

Approximately 95 percent of currently produced room air conditioners use the so-called rotary (rolling piston, stationary vane type) compressors. The majority of these compressors are driven by single-speed 3500 RPM, two-pole, single-phase, PSC-type induction motors (for commercial applications, a limited selection of three-phase models are also available). As discussed in Section 2, this is the least costly high-efficiency configuration for single-phase induction motors, because a separate starting capacitor and relay is not required. However, the starting torque is limited. The air conditioner off cycle must be long enough to allow refrigerant to bleed through the capillary tube to the evaporator, allowing high and low side pressures to equalize, before attempting to restart the compressor.

According to [Dickey, 1994], motor efficiencies in currently produced compressors range from 84 to 89 percent. The range reflects the fact that compressors are produced in a finite number of shell diameters and consequently, a finite number of motor stator and rotor diameters. At a fixed motor diameter, ranging the length of the lamination stack varies the motor output and increases the efficiency variation. Current motor efficiencies are already close to practical limits, with an additional increase in efficiency of about one to two percentage points being feasible, through design modification and the use of lower loss motor lamination steel.

3.2.4.2 Fan/Blower Motor

The fan motor consumes approximately 10 to 15 percent of the input energy to a room air conditioner. Typically, two- or three-speed motors are used to provide a degree of capacity control and quieter operation at the lower fan speeds. According to [Beard, 1994], the majority of RACs produced today use PSC motors to drive the fans, with respectable full-speed efficiencies of 50 to 70 percent, depending on the capacity and number of fan speeds. This range of efficiencies is close to the practical limit for induction motors. However, low-speed efficiencies are considerably less. The actual motor power consumption does not decrease significantly at the lower speeds. As discussed above, an ECPM motor would operate at an increased full-speed efficiency (by 10 to 15 percent on average) and at a significantly increased low-speed efficiency compared to standard multiple-speed PSC motors.

3.2.4.3 Efficiency Improvement and Energy Savings Potential

Tables 3-13 and 3-14 summarize the potential national energy savings and the payback that could be realized through application of incrementally higher-efficiency motors or variable-speed motors. Potential energy savings of 15 percent were assumed for a variable-capacity, compressor blower/fan (approximately half of the savings obtained with variable speed in central air conditioners).

Table 3-13: Potential for Energy Savings Through Increased-Efficiency Room Air Conditioner Motors (Base Site Motor Energy[1] = 29 x 10^9 kWh/yr)

Motor (Base Energy, 10^9 kWh/yr)	Current Motor Efficiency (%)	Efficient Motor Option	Possible Efficiency (%)	Estimated Annual Energy Savings[2]		
				On-site		Primary 10^{12} Btu
				Percent	10^9 kWh	
Compressor (25)	87	Higher-Efficiency PSC	89	2.2	0.6	6
		Variable-Speed ECPM[3]	90	10	2.5	28
Fan/Blower (4)	60	Variable-Speed ECPM	75	50[4]	2	22

1 Base Site Motor Energy–the estimated annual motor site electric energy consumption for this application, based on the efficiency of all motors in the installed base (Table 3-1).
2 Energy savings based on application of efficient motor option to the entire installed base, compared to base energy
3 In conjunction with a variable-speed ECPM evaporator fan
4 Energy savings include reduced compressor energy due to reduced cooling load, more efficient low speed operation

Table 3-14: Cost-Effectiveness of Efficient Motor Options for Room Air Conditioners—Estimated Payback for Average User at Average Electricity Rate ($0.08/kWh)

Motor	Average UEC kWh/yr	Efficient Motor Option	Energy Savings		Additional Retail Cost, $	Simple Payback, Years
			Percent	$/yr		
Compressor	900	Higher-Efficiency PSC	2.2	1.60	20	13
Fan/Blower	100	ECPM Variable Speed[1]	10	7.20	200	20+
		Variable ECPM Speed[2]	50[2]	4.00	40	10

1 Used with a variable-speed ECPM evaporator fan, included in the “additional retail cost”

2 Energy savings include reduced compressor energy due to reduced cooling load, more efficient low speed operation

3.2.5 Clothes Washers

The estimated electric energy consumption of the drive motor for residential clothes washers is somewhat more than 2 percent of the total motor electric energy consumption in the residential sector. The typical washer drive motor is a 1/2 or 3/4 hp, two-speed 1725/1140 RPM single-phase induction motor, with the lower speed used to operate a “gentle” or “delicate” cycle. At the typical efficiency levels of 60 percent to 65 percent, there is some margin for increase. However, with a typical duty cycle of only 200 hours per year, the higher cost, higher-efficiency motor will not be cost-effective (200 hours x 50W saved = 10 kWh/year or about $1 worth of energy cost savings). Energy for heating the hot water is a much more significant part of the total energy input to a clothes washer. Hot water energy is more than 90 percent of the total energy input even at the current standard level which eliminates hot rinses and significantly limits warm rinses.

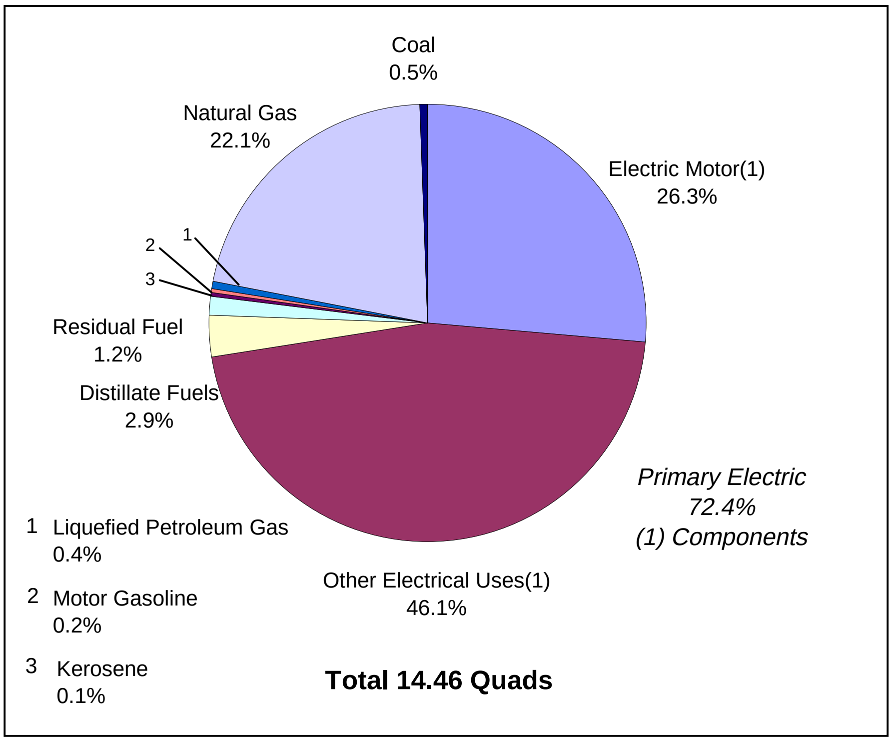
In the NAECA standards that established the current minimum efficiency for clothes washers, one of the design options considered was increasing the efficiency drive motor from 65 percent in the base case to 75 percent (the difference between standard level 1 and 2). The resulting incremental retail price increase of an average washer was estimated to be $11.60 (in 1987 $), with calculated annual energy cost savings of $1.10 (also in 1987 $), and a resulting payback period of 10 years.

4 Motor Populations, Energy Usage, and Savings Potential in the Commercial Sector

As shown in Figure 4-1, electric energy consumption in the commercial sector accounts for over two-thirds of total sector primary energy consumption. Electric motors consume about 36 percent of the total electric energy consumed in the commercial sector. As discussed below, commercial refrigeration and space conditioning, including both HVAC Compressors and HVAC Thermal Distribution, together account for 93 percent of motor energy consumption in the sector. The major applications of electric motors energy-use are discussed below in detail.

Figure 4-1: 1995 Commercial Energy Consumption by Fuel Type

Category	Energy Consumption	
	Quads	Percent
Primary Electric[1]	10.47	72.4%
Electric Motors[2]	*3.8*	*26.3%*
Other Electrical Uses[2]	*6.67*	*46.1%*
Distillate Fuels	0.47	3.3%
Residual Fuel	0.17	1.2%
Liquefied Petroleum Gas	0.07	0.5%
Kerosene	0.02	0.1%
Motor Gasoline	0.07	0.5%
Natural Gas	3.11	21.5%
Coal	0.08	0.6%
Renewable Energy	0.00	0.0%
Total	**14.46**	**100%**



Sources: AEO 1998. Electric to primary energy conversion: 1 kWh = 11,005 Btu

1 Includes generation, transmission, and distribution losses

2 Both components of the Primary Electric component

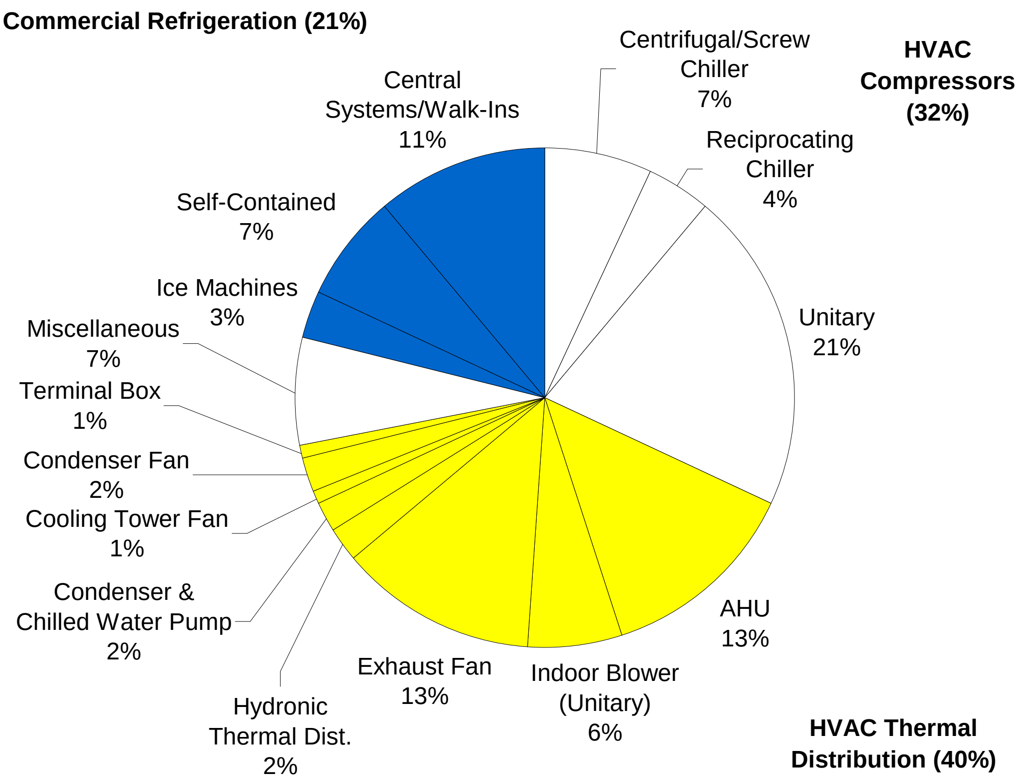
4.1 Commercial-Sector Motor Population and Energy Usage

Electric motor applications consume more than one-quarter of commercial-sector primary energy and somewhat less than 40 percent of commercial-sector electric energy (with much of the remainder being used for lighting and electric resistance heating). On-site electric energy consumption of commercial-sector electric motors in 1995 was approximately 345 billion kWh annually; the corresponding primary energy consumption being 3.8 quads. As shown in Figure 4-2, about 93 percent of commercial-sector electric motor energy is consumed in two major applications: commercial refrigeration and space conditioning, including HVAC Compressor and HVAC Thermal Distribution.

The remaining commercial-sector motor energy consumption is shared among various miscellaneous applications including small motors in office equipment, commercial laundry, and vertical transportation. None of these categories accounts for more than 1.5 percent of motor energy consumption in the commercial sector. There is a variety of commercial space conditioning and commercial refrigeration equipment used in industry. The major categories are discussed below.

As discussed in section 3.1, federally mandated energy efficiency standards have had a profound effect on the efficiency of the electric motors used in the major residential sector motor energy consuming applications. In contrast, in the commercial sector, the Energy Policy Act of 1992 (EPAct) and ASHRAE Standard 90.1 have set minimum efficiency standards for a subset of motor-using space conditioning equipment, but no standards for commercial refrigeration equipment. In comparison with the aggressive efficiency standards under NAECA for residential refrigerators and air conditioners, EPAct and ASHRAE 90.1 standards for commercial air conditioning equipment are considerably less stringent. Consequently, they are not the potent drivers of OEM motor efficiencies that NAECA standards have been for residential motor applications.

Figure 4-2: 1995 Commercial-Sector Motor Energy Usage (Primary Energy 3.8 quads)



Sources: ADL Estimates; ADL, 1996; ADL, 1998(a); Table 4-2; Table 4-4

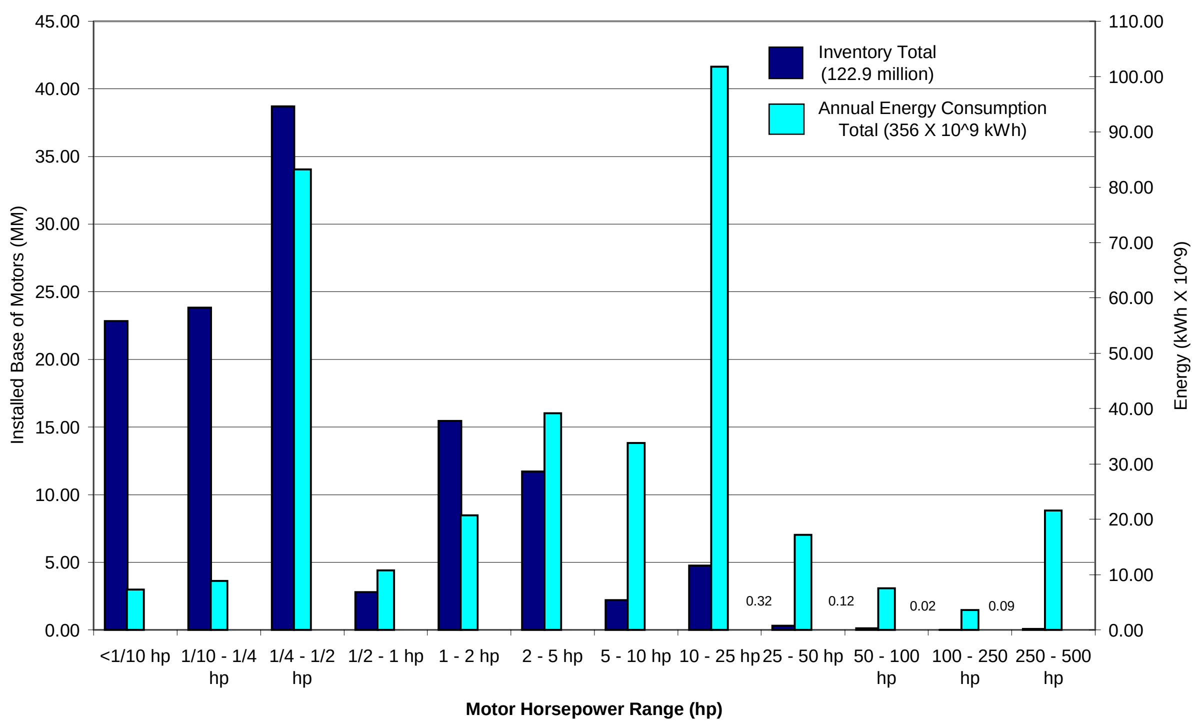
The average rated output of motors that consume a large fraction of commercial-sector energy is considerably higher than in the residential sector (approximately 10 hp vs. 1 hp). As shown in Figure 2-3, the efficiency of a “low” efficiency 10 hp motor is only seven percentage points lower than the best model commercially available.

The population and energy consumption of electric motors in commercial applications is depicted graphically in Figure 4-3. The total nominal output of the installed base for these motors is approximately 341 million hp, and recent annual sales of new motors for commercial-sector applications total approximately 50 million hp. In both the residential and commercial sectors, the vast majority of the motors are installed by OEMs in comfort conditioning products, major appliances, or small appliances. Even in larger motor sizes, OEMs purchase more than half of integral horsepower, polyphase, AC induction motors.[1] In the commercial sector, fractional horsepower motors are a small

[1] DOE, 1996

portion (approximately 8 percent) of the installed horsepower base. Within this base, motors below 20 hp account for approximately 42 percent of the total while motors above 20 hp account for approximately 58 percent of the total installed horsepower base. This contrasts significantly with the industrial sector, where previous studies have estimated that 72 percent of motor energy is consumed by motors of over 50 hp capacity (only 5 percent of the motor population).

Figure 4-3: 1995 Commercial Building Sector Motor Inventory and Motor Energy Consumption by Horsepower Range for Major Applications

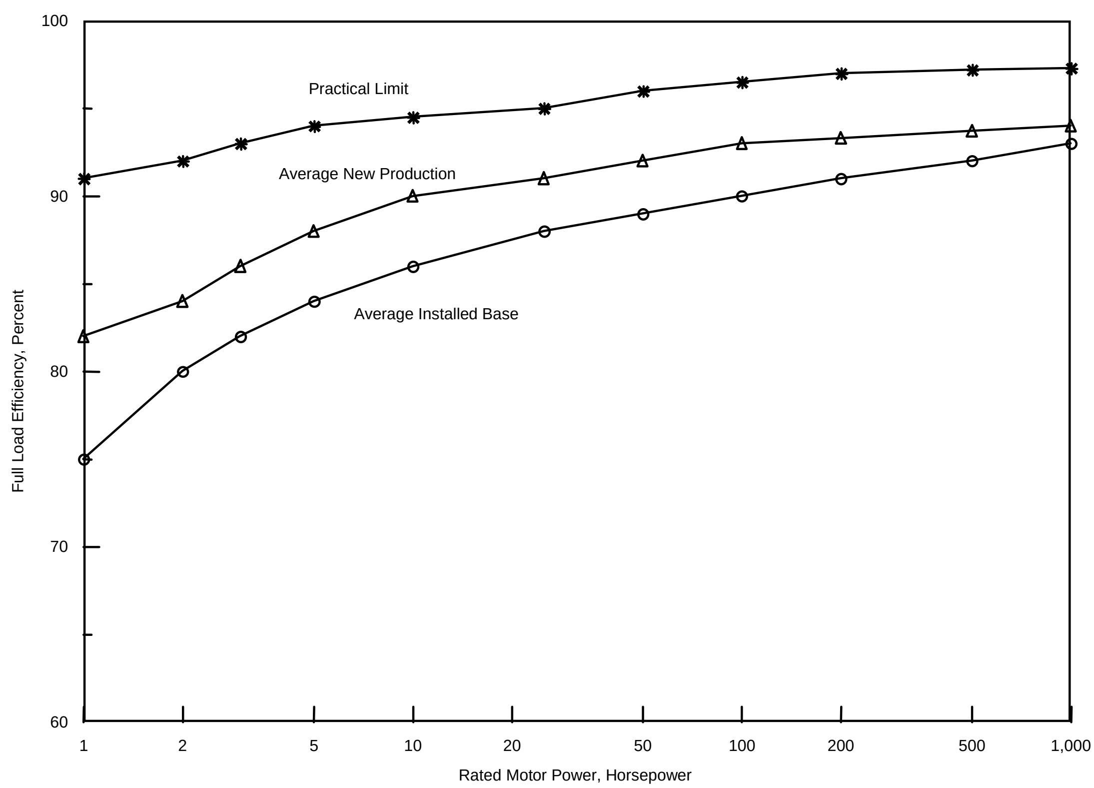


Sources: Tables 4-1 to 4-21

A broad understanding of motor efficiency distribution can be obtained by comparing the average installed base efficiency and average new production with the minimum efficiency levels established by EPAct and influenced by NAECA. A further comparison can be made with the practical limits of induction motors to determine the unrealized efficiency gains. Figures 4-4 plots these efficiency levels for the commercial-size motors. At power levels above 20 hp, the efficiency difference between “low” and “high” efficiency motors declines to five or six percentage points (see a discussion of the cost-effectiveness of specifying incrementally higher-efficiency three-phase motors in Section 2).

In the commercial sector, the efficiency of the installed base will be upgraded in similar, but more gradual fashion, due to EPAct and ASHRAE Std. 90.1. Under the EPAct-mandated standards that took effect in October 1997, previous NEMA efficient motors are the minimum efficiency permitted for sale, applied to general-purpose integral horsepower polyphase AC induction motors.

Figure 4-4: Comparison of the Efficiency of Three-Phase Induction Motors



Source: ADL Estimates; MotorMaster+ 3.0

4.2 Commercial-Sector Motor Energy Savings Potential

From the preceding section, commercial refrigeration and space conditioning, including space cooling and heating, thermal distribution for space cooling/heating, and ventilation, together account for 93 percent of motor energy consumption within the commercial sector. These two applications are in widespread use and involve significant motor power and relatively high duty cycles, typically more than two thousand operating hours per year.

In this section, the commercial-sector energy savings potential and cost-effectiveness are evaluated for:

- Incrementally increasing the efficiency of motors
- Application of adjustable-speed drives, where appropriate

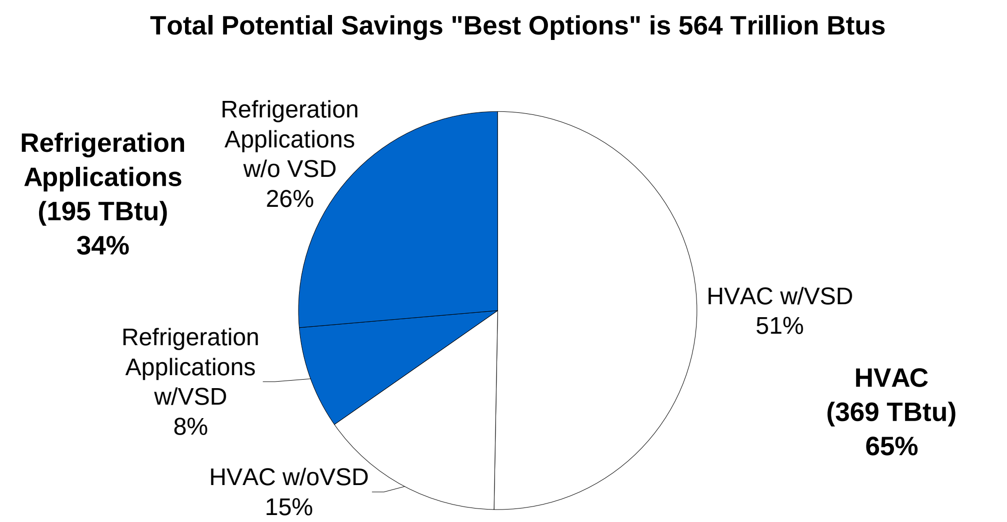
The opportunities to save energy are evaluated in terms of their energy saving potential, cost-effectiveness (at current cost levels), and the potential to improve the cost-effectiveness. Note that variable-speed drives are not evaluated for HVAC compressor applications for the reasons given below, and that background data for HVAC thermal distribution estimates are shown for incrementally higher-efficiency motors, not variable-speed drives.

Figure 4-5 summarizes the commercial-sector savings potential: about 564 trillion Btu of energy savings potential is estimated to exist, with 65 percent of the savings from HVAC applications. Figure 4-6 shows that the use of incrementally efficient motors generally carries an attractive payback in the commercial sector: over 85 percent of the technical savings potential has an estimated payback of under three years. Approximately 324 trillion Btus, over 90 percent of the potential savings, has a payback less than five years.

Although the total estimated commercial-sector savings is only about 35 percent that of the residential sector (see Fig. 3-7), the measures are significantly more cost-effective in a number of cases, most options having paybacks of three years or less. When only measures with a payback of five years or less are considered, the savings potential of the residential and commercial sectors are roughly equivalent (see the Executive Summary). Certain refrigeration applications such as the use of ECPMs in driving refrigerator fans have particularly short paybacks, generally less than two years.

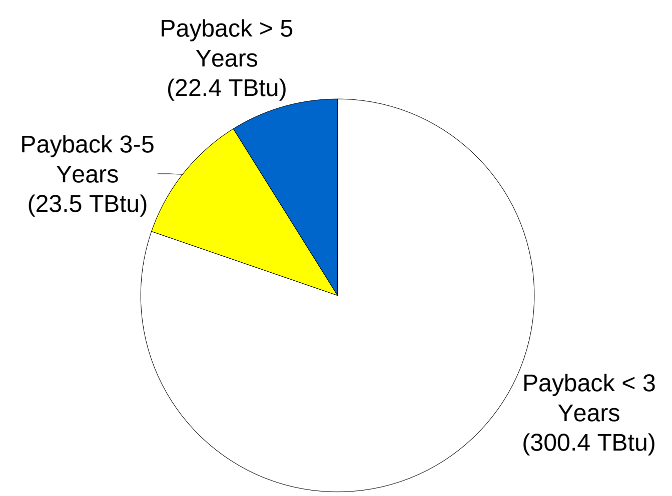
In HVAC applications, the 1997 implementation of EPAct motor efficiency standards appears to have been at least partially responsible for the presence of relatively small price differentials between high-efficiency motors and those of standard efficiency (the minimum EPAct efficiency for general purpose three-phase motors—see Table 2-1). This results in reasonable paybacks for a number of HVAC measures, primarily in applications driving fans and pumps. Many of the compressor motor replacement measures currently tend to have paybacks in the range of five years. Note, however, that at the time of this writing, EPAct efficiency standards were in place less than a year. Consequently, price differentials will continue to change, stabilizing with fewer linearity issues across the motor size range examined.

Figure 4-5: Allocation of Commercial Motor Savings Potential



Sources: Tables 4-2, 4-4, 4-6, 4-8, 4-10, 4-12, Figure 4-7

Figure 4-6: Payback Period for Increased-Efficiency Motors in Commercial Applications



Sources: Tables 4-2, 4-4, 4-6, 4-8, 4-10, 4-12 through 4-21

Assumptions: 11,005 Btu/kWh heat rate; $0.08/kWh electric rate [DOE, 1998]; application of variable-speed drives not included
Equipment Not Included: Roll-in Refrigerators & Freezers, Other Refrigerators/Freezers, Small Grocery

Figures 4-5 and 4-6 are based on the calculations noted in the tables in this section. The savings for refrigeration applications noted in Figure 4-5 are slightly less than those noted in Table 4-12. This is to account for the fact that compressor motor and evaporator fan motor savings cannot be summed directly. Higher compressor motor efficiencies result in a lowering of potential savings for evaporator fan motors. Savings for some measures have been reduced by about 5 percent, where appropriate, to estimate the result of this effect. Note also that in the following tables, two sets of baseline efficiencies are used for two purposes. The calculations of energy savings are based on a comparison between high-efficiency motors and the estimated efficiency of the installed inventory. Calculations of payback, however, compare high-efficiency motors to the standard motor efficiencies now available, which are generally near EPAct minimums. This reflects the actual economic choices that would be made currently in evaluating a replacement for a failed motor. The $0.08/kWh electric rate used in the calculations is the 1996 average rate for the commercial sector [DOE, 1998].

Because each of the main three subgroups (compressors, thermal distribution, and refrigeration) varies considerably in its technology, constitution of stakeholders and energy savings potential, the subgroups are treated separately in sections 4.2.1, 4.2.2 and 4.2.3, respectively.

4.2.1 Air Conditioning Compressors

Air conditioning equipment used in the commercial sector covers a wide range of cooling capacities (from 1 ton to several thousands of tons) and systems, as summarized in Table 4-1, and consumes nearly 1.7 quads of primary energy (Figure 4-2). This diversity of systems includes small packaged systems (residential type room air conditioners, packaged terminal air conditioners, and residential central systems), larger

Table 4-1: 1995 Commercial Air Conditioning Equipment Compressor Motor Characteristics

Type of System	Annual Unit Sales[2]	Average Lifetime[1]	Installed Base[5]	Capacity Range, Tons	Motor Power Range, hp	Motor Efficiency Range
Room Air Conditioner	829,860	11	9,128,460	1¼ and higher	1/2 – 3	80 - 88
PTAC[3]	212,418	15	3,186,270	1/2 - 1 1/2	1/2 – 2	80 - 85
Small Unitary[4]	589,100	15	8,836,500	2 - 5	2 – 5	80 - 90
Medium Unitary[4]	169,118	15	2,536,770	5 - 20	5 – 20	82 - 92
Large Unitary[4]	16,040	15	240,600	20 - 100	20 – 100	85 - 92
Reciprocating Chiller	13,000	20	210,000	10 - 150	7 1/2 – 150	85 - 92
Screw Chiller	2,500	20	20,000	50 - 1,000	40 – 750	90 - 94
Centrifugal Chiller	10,087	23	90,000	75 - 8,000	50 - 6,000	90 - 96
Absorption Chiller	500	23	8,000	100 - 1,500	None	N/A

Sources: 1 DOE, 1998
2 USCB, 1995(b)
3 Includes Packaged Terminal Heat Pumps
4 Single Packaged A/C and Year-round Packaged A/C.
5 ADL Estimates based on annual unit sales and average unit lifetimes

unitary systems (primarily rooftop systems) and chillers. The majority of the energy is consumed by large tonnage systems with large (>10 hp) drive motors. In general, the smaller systems are constant-capacity (single-speed, fixed-displacement, and single-compressor), while the larger systems incorporate some form of capacity modulation (e.g., multiple compressors, cylinder unloading, screw compressor slide valves, or centrifugal compressor pre-rotation vanes).

In currently produced equipment, with few exceptions, the drive motors are single speed, three phase induction motors with efficiencies that approach within a few percentage points of practical limits. Thus, the opportunity to improve air conditioning efficiencies through continuous variable capacity operation, instead of the full capacity on/off operation, is one that has largely been implemented in the commercial sector (with the exception of small-capacity systems). The maximum technical potential for primary energy savings across the entire installed compressor base (using incrementally higher-efficiency motors) is approximately 76 trillion Btu (Table 4-2). This potential will be realized as older equipment is retired and replaced with equipment that is more efficient.

Table 4-2: Potential Energy Savings With Incrementally Higher-Efficiency Commercial Air Conditioning Compressor Drive Motors

Type of System	Annual Operating Hours	Current Energy Consumption 10^9 kWh[7]	Efficiency (%)		Energy Savings		Payback
			Current	Possible	Site 10^9 kWh	Primary 10^{12} Btu	
Room Air Conditioner[1]	1000	7.8	87	90	0.23	2.5	5.9
PTAC[1]	1000	2.9	82	90	0.23	2.5	5.9
Small Unitary[2]	1000	23.3	85	93	1.9	20.9	1.6
Medium Unitary[3]	1200	26.1	87	94	1.8	19.8	4.5
Large Unitary[4]	1500	15.1	89	95	0.9	9.9	1.5
Reciprocating Chiller[4]	1500	13.2	89	95	0.8	8.8	1.5
Screw Chiller[5]	1500	3.6	92	96	0.1	1.1	5.0
Centrifugal Chiller[6]	1500	21.6	93	97	0.9	9.9	5.8
Total	—	**113.6**	—	—	**6.9**	**75.9**	—

Assumptions: Energy savings are calculated based on efficiencies shown, reflecting actual savings seen when replacing installed base with new motor. Payback is calculated based on costs and efficiencies from Table 2-1.
Sources: Tables 2-1 and 4-1
1 Based on 1 hp motor
2 Based on 3 hp motor
3 Based on 10 hp motor
4 Based on 50 hp motor
5 Based on 150 hp motor
6 Based on 200 hp motor
7 *Calculation: Installed base * annual operating hours * [(assumed hp / efficiency) * 0.746]*

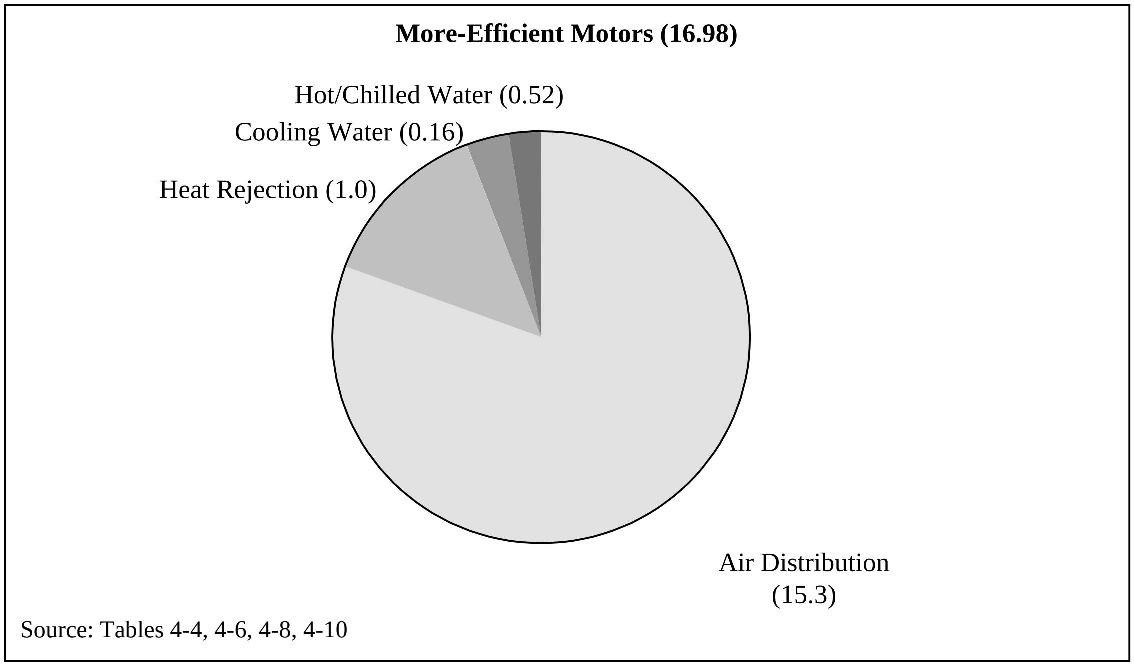
4.2.2 Space Conditioning Thermal Distribution

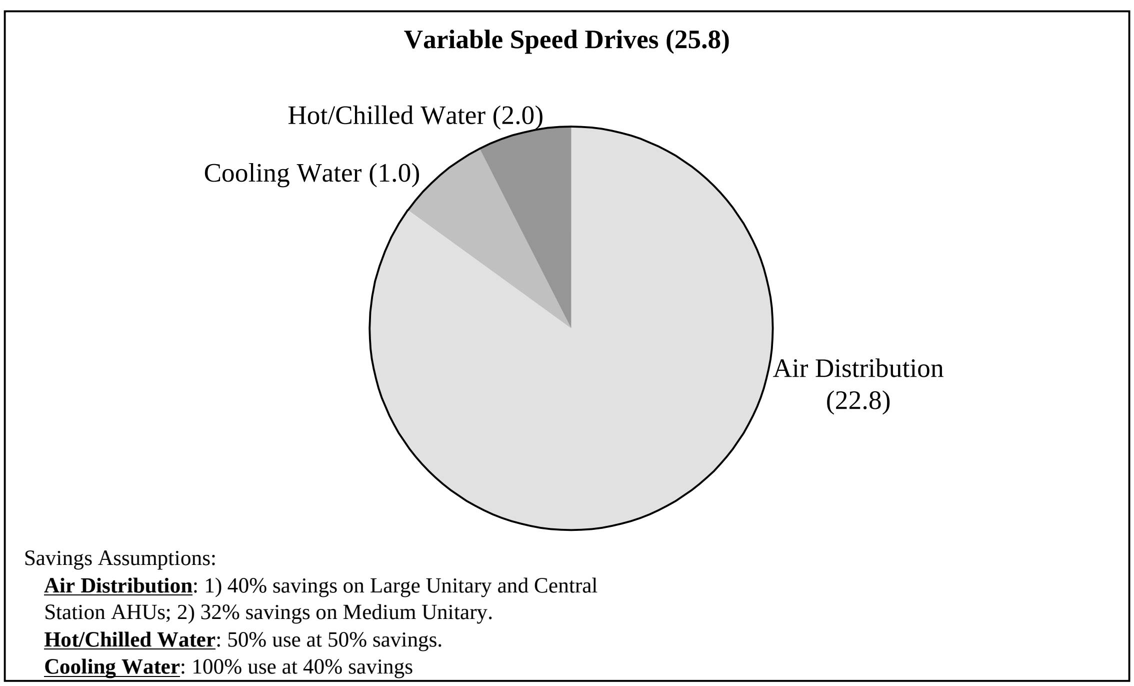
Thermal distribution in commercial buildings encompasses four basic areas: heated/cooled/ventilation air distribution, chilled and hot water distribution, cooling water circulation, and heat rejection to ambient air (via condensers and cooling towers). As in the case of commercial buildings and their equipment, various thermal distribution systems are in use. Examples of these include small capacity, residential type, ducted and non-ducted air distribution systems, such as window air conditioners, PTACs, and small unitary systems, to large, complex hydronic systems including large air handlers with extensive ductwork. An exhaustive treatment of this area is beyond the scope of this study, but the estimates developed below indicate that this is a promising energy savings area that should be examined. Again, the focus of this work is on the blower or pump drive motor and the opportunity for energy savings through motor enhancements such as higher-efficiency and variable-speed operation. Space conditioning energy consumption and thermal distribution motor energy consumption are affected by many other factors such as duct and pipe cross sections, duct leakage, insulation effectiveness, and control schemes that overcool and reheat the air. These factors would merit a comprehensive, system level evaluation, but are outside the scope of this work.

For this work, a limited range of typical configurations represents the complexity and variety of commercial building thermal distribution systems. Air and water distribution systems are discussed below in separate sections, but a basic consideration common to both is that part-load energy consumption can be reduced significantly with variable flow systems.

Approximately 100 billion kWh is consumed on site (equivalent to about 1.1 quads primary) to drive fans and blowers used for a variety of functions. Some examples include the distribution of heated and cooled air within commercial buildings, to reject heat from commercial building air conditioning systems, to distribute hot and chilled water and to circulate HVAC system cooling water. This large magnitude (about two-thirds of commercial building air conditioner compressor power consumption) reflects the fact that heating and cooling effects often have to be transported over long distances in commercial buildings. Significant energy savings are possible through this motor technology, particularly with the applications of variable-speed blower drives to interior conditioned air distribution. In new installations, the incremental investment in a variable-speed drive for air handling is generally cost-effective, with payback periods ranging from two to five years. The makeup of the potential savings is illustrated in Figure 4-7. This savings is accomplished through either more-efficient motors or adjustable-speed drives.

Figure 4-7: Potential Energy Savings From More-Efficient Motors and VSDs in Commercial Thermal Distribution (Site kWh x 10^9)





4.2.2.1 Air Distribution

As described in [Sun, 1993] there is a considerable variety of commercial building air-distribution configurations. The following are currently the most commonly used:

- Local recirculating systems with small packaged equipment such as room air conditioners and PTACs with room fan coil units

- Ducted air distribution from small, residential-scale, unitary air conditioning systems, which usually also include a heat source (gas furnace, heat pump, or electric resistance); The blower speed and airflow rates are generally constant, operating in an on/off mode in response to a cooling or heating demand.

- Ducted air circulation systems from rooftop unitary systems, similar to a residential central air conditioning system (but larger); Rooftop air conditioners are available in single-zone and multi-zone configurations (with each zone typically having a dedicated interior air blower), with constant or variable air volume. From the viewpoint of motor efficiency and motor energy consumption, zoning is not an important distinction but, as discussed below, variable-air-volume systems will use less energy seasonally. The vast majority of these systems are constant-air-volume systems.

- Constant-air-volume central station air handlers supplying large ducted air distribution systems; As the name implies, blowers operate continuously at full output, supplying both heated and cooled air blended, as needed, in individual zones to maintain the desired temperature.

- Variable-air-volume central station air handlers used in large commercial buildings where heating and cooling are needed simultaneously within the building; Airflow rates are varied in response to a demand for heating or cooling.

Table 4-3 estimates the installed base of commercial-sector interior air distribution fan and blower motors. Table 4-4 provides an estimate of blower-motor energy consumption and potential savings through specifying increased efficiency motors. Generally it is cost-effective to specify a higher-efficiency motor instead of a lower-efficiency motor, but not cost-effective to carry out an early retrofitting of a high-efficiency motor in place of a lower-efficiency one.

Table 4-3: Motors in Commercial-Sector Interior Air Distribution (Space Cooling and Space Heating—1995)

Type of System	Annual Unit Sales[2]	Average Lifetime[1]	Installed Base[5]	Blower Motor	
				Horsepower	Efficiency
Room Air Conditioner	829,860	11	9,128,460	1/10 – 1/3	50 – 70
PTAC[3]	212,418	15	3,186,270	1/10 – 1/4	50 – 70
Small Unitary[4]	589,100	15	6,193,029	1/4 – 3/4	60 – 80
Medium Unitary[4]	169,118	15	1,780,161	1 - 5	70 – 85
Large Unitary[4]	16,040	15	167,113	5 - 25	80 – 90
Exhaust Fan	836,238[6]	15[6]	12,543,576[6]	1/4 – 3/4	60 – 80
Room Fan Coil	234,650	15	3,519,750	1/10 – 1/4	50 – 70
Central Station AHU	336,207	15	1,780,429	5 - 25	80 – 90

Sources: 1 DOE, 1998
2 USCB, 1995(b)
3 Includes Packaged Terminal Heat Pumps
4 Single Packaged A/C and Year-round Packaged A/C.
5 ADL Estimates based on annual unit sales and average unit lifetimes
6 Estimate based on ADL, 1998(a) energy usage calculation.
*Calculation: Base = Energy Consumption (in kWh) / [(Effective Full Load Hours of 5681 ave) * [(Assumed hp of 0.5 / Assumed Efficiency of 60 percent) * 0.746]]*

Table 4-4: Potential Energy Savings With Incrementally Higher-Efficiency Interior Air Distribution Blower Drive Motors—Commercial Buildings

Type of System	Typical Annual Operating Hours	Current Energy Consumption 10^9 kWh[6]	Efficiency %		Savings		Payback Period (yrs)
			Current	Possible	Site 10^9 kWh	Primary 10^{12} Btu	
Room Air Conditioner[1]	1000	1.9	60	75	0.3	3.3	7.7
PTAC[1]	1500	1.2	50	75	0.3	3.3	2.6
Small Unitary[2]	2000	7.7	60	80	1.5	16.5	0.0
Medium Unitary[3]	2500	8.3	80	90	0.8	9.1	0.4
Large Unitary[4]	3000	4.4	85	92	0.3	3.3	0.6
Exhaust Fan[2]	5681[5]	44.3	60	80	8.9	97.9	0.0
Room Fan Coil[1]	2000	1.8	50	75	0.5	5.5	2.2
Central Station AHU[4]	3000	45.8	87	93	2.7	29.7	0.7
Total	—	115.4	—	—	15.3	168.6	

Assumptions: Energy savings are calculated based on efficiencies shown, reflecting actual savings seen when replacing installed base with new motor. Payback is calculated based on costs and efficiencies from Table 2-1.

Sources: Tables 2-1, 2-3 and 4-3

1 Based on 1/6 hp ECPM vs. PSC motor with 100 percent retail markup.
2 Based on 1/2 hp induction motor. [Grainger] indicates no cost differential for high-efficiency motor
3 Based on 2 hp motor
4 Based on 10 hp motor
5 Based on average from ADL, 1998(a) for Exhaust Fan EFLH
6 *Calculation: Installed base * annual operating hours * [(assumed hp / efficiency) * 0.746]*

Variable-air-volume systems save air motive power by varying the airflow rate in proportion to the heating and cooling loads. In addition, variable-air-volume systems provide significant energy savings because they minimize overcooling and reheating of conditioned air. The focus here is on air-moving blower motor energy savings.

The inherent blower power savings available in variable air volume systems are illustrated in system curves which plot typical system static pressure loss vs. flow rate and the corresponding air moving power. These curves are typical of complex air distribution systems where a constant air supply pressure is maintained at the diffusers where conditioned air is introduced into the conditioned space as demanded by heating or cooling requirements. In simpler distribution systems, where no minimum static pressure is required at the diffusers, the pressure-flow and power-flow curves follow a flow-squared and flow-cubed relationship, respectively. The air moving power at 1/2 flow will only be 1/8 of the full flow power in this system.

Airflow rates are varied in VAV systems using several basic methods:

- Output throttling, e.g., with a motorized damper (the least efficient way)
- Inlet guide vanes (more efficient than throttling)
- Variable-ratio transmissions between the motor and blower shaft (efficient)
- Variable-speed drive of the blower motor (most efficient)

The first two of these techniques vary the air flow rate by throttling or partially throttling the air flow, and as a result, fail to realize significant motor energy savings. In addition, since these techniques do not involve enhanced motor performance, they are outside the scope of this study. Varying the airflow rate using a variable-speed blower drive does realize significant energy savings because the speed-pressure-flow characteristic of the blower matches the flow-pressure loss characteristic of the duct systems.

In a simple, ducted air distribution system operated in an on/off mode, significant savings, greater than half the blower energy, can be realized by a continuous variable-speed operation, capacity modulated mode. This is essentially the residential central air conditioning operating mode discussed in Section 3.2.3. A capacity modulated cooling and heating source is needed along with the variable-speed blower motor.

In applying a variable-speed drive to a more complex, large building air distribution system, less energy savings are realized because a minimum air supply pressure must be maintained at the diffusers, regardless of the demand. Nevertheless, energy savings between 25 and 40 percent of the input energy to a throttled VAV can be realized. On average, the payback period on the investment in an inverter drive for a variable-speed motor is only a marginally attractive five years [ACEEE, 1991]. Electric utility rebate programs have played a major role in many VSD applications in this area.

In a pilot study of VSDs performed by the EPA for the Energy Star Buildings program [EPA, 1993], surveys and field tests were conducted in 10 buildings around the country. In comparison to variable-inlet vanes (VIVs), VSDs provided an average energy savings of 52 percent and average demand savings of 27 percent.

The average, simple payback period was two and a half years. The following were the major lessons learned from the experiments:

- VSDs are usually profitable, especially if the existing fan is oversized.
- The benefits are diminished if the fan runs at or near the rated capacity for long periods.
- Backward-inclined airfoil fans are the best candidates for VSDs. Forward-curved fans become unstable and are difficult to control at lower speeds.

Also, to limit power quality degradation, VSDs should be equipped with:

- Internal power factor correction capacitors
- Integral harmonic filters to reduce the total current harmonic levels to within 5 percent

To estimate the energy savings potential of VSDs, the following assumptions are used:

- 80 percent of Medium Unitary Systems are candidates for VSDs. For VSD potential applications, energy savings are estimated at 40 percent.
- 100 percent of all Large Unitary and Central Station AHUs are candidates for VSDs. VSDs result in 40 percent energy savings.

As shown in Figure 4-7, the total potential energy savings from VSDs in interior air distribution blower systems is 23 billion kWh.

4.2.2.2 Hydronic Hot and Chilled Water Circulation/Distribution

Hydronic thermal (chilled water and hot water) distribution systems tend to be used in fairly large systems, with pump motor power ranging from 1 to 25 hp. Tables 4-5 and 4-6 summarize the energy use and potential energy savings. The majority of the systems contain reasonably efficient three-phase motors, generally within five percentage points or closer of the best available motor efficiency. At partial cooling or heating loads, the water circulation rate could be reduced with a variable-speed drive resulting in significant energy savings. To gain these significant savings, the entire hydronic distribution system must be designed to operate in a variable flow/variable head mode. Larger horsepower systems represent the most cost-effective applications for VSDs, because inverter cost per horsepower is lower and the cost of controls is spread over a greater potential savings base.

Table 4-5: Motors in Commercial-Sector Hydronic Thermal Distribution (1995)

Type of Air Conditioning System	Annual Unit Sales[2]	Average Lifetime[1]	Installed Base[3]	Pump Motor - Typical	
				Horsepower (hp)	Efficiency (%)
Centrifugal Chiller	10,087	23	90,000	20	90
Screw Chiller	2,500	20	20,000	15	90
Reciprocating Chiller	13,000	20	210,000	5	88
Absorption Chiller	500	23	8,000	25	90
Hydronic Boiler	15,186[4]	23	350,000	15	90

Sources: 1 DOE, 1998
2 USCB, 1995(b)
3 ADL Estimates based on annual unit sales and average unit lifetimes
4 ADL Estimates based on [Appliance 1998]

Table 4-6: Potential Energy Savings With Incrementally Higher-Efficiency Drive Motors for Hydronic Circulation Pumps in Commercial Buildings

Type of System	Typical Annual Operating Hours	Current Energy Consumption 10^9 kWh[3]	Motor Efficiency (%)		Annual Savings		Payback (years)
			Current	Possible	Site 10^9 kWh	Primary 10^{12} Btu	
Centrifugal Chiller[1]	1500	1.3	90	95	0.1	1.1	0.6
Screw Chiller[2]	1500	0.1	90	94	0.01	0.1	2.2
Reciprocating Chiller[2]	1500	1.2	88	93	0.1	1.1	1.7
Absorption Chiller[1]	1500	0.1	90	95	0.01	0.1	0.6
Hydronic Heating[2]	1500	6.4[4]	90	94	0.3	3.3	2.2
Total	—	9.1	—	—	.52	5.7	—

Assumptions: Energy savings are calculated based on efficiencies shown, reflecting actual savings seen when replacing installed base with new motor. Payback is calculated based on costs and efficiencies from Table 2-1.

Sources: Tables 2-1 and 4-5
1 Based on 25 hp motor costs and efficiencies.
2 Based on 10 hp motor
3 *ADL Estimate based on the calculation: Installed base * annual operating hours * [(assumed hp / efficiency) * 0.746], and a factor of 0.48 for pumps.*
4 *ADL Estimate based on the calculation: Installed base * annual operating hours * [(assumed hp / efficiency) * 0.746], and a factor of 1.5 for heating pumps*

A rough estimate of the potential energy savings for a variable-speed/variable flow hydronic system can be made by equally distributing the operating hours over a capacity range from 100 percent to 25 percent of the design flow. Since the hydronic distribution system includes fixed resistances, the power-flow rate cubed relationship provides a reasonably accurate model of system behavior. In this instance, allowing for inverter efficiency at full and part load, the energy savings would be 50 percent as compared to a constant flow system. The potential savings are approximately 2-3 billion kWh based on the assumption that a majority of the installations could use this type of variable-speed/variable flow system. For a 10 hp pump, operating 2,000 hours per year, at 8¢/kWh, electric energy consumption would be 16,700 kWh/year and energy costs will be $1,330/year. The price of the 10 hp inverter is approximately $1,500, with inverter costs continuing to decrease gradually. Control of the pump speed is based on maintaining a 10°F difference between the return and supply water temperatures. Assuming a total cost of $2,000 for inverter and controls, the simple payback period would be three years. The payback will vary depending on the electric rate structure, the annual operating hours, and the motor horsepower. Smaller motors have a longer payback because inverter costs per horsepower are higher for these motors.

4.2.2.3 Cooling Water Circulation

Several important classes of commercial air conditioning equipment are commonly water-cooled:

- Centrifugal chillers (approximately 90 percent)
- Screw chillers (approximately 70 percent of installed base; approximately 45 percent new production)
- Reciprocating chillers (approximately 50 percent)
- Lithium bromide—water absorption chillers (100 percent)
- Some condensing units used with direct expansion evaporators (few systems)

By far, the most common source of cooling water is a cooling tower, which rejects heat at the ambient wet bulb temperature and is connected to the chiller with a closed water circulation loop. In the typical cooling water loop, constant cooling water circulation is maintained when the air conditioning equipment is operating. The installed base and annual sales of cooling water pump motors are summarized in Table 4-7. The energy consumption and potential for savings with high-efficiency, constant-speed motors is estimated in Table 4-8. The potential savings from specifying the highest available efficiency motors compared to typical efficiencies in new equipment are small. Based on 2,000 operating hours per year, specifying higher-efficiency motors is cost-effective (see Table 2-1), with payback periods of one to three years.

Table 4-7: Cooling Water Circulation Pump Motors in the Commercial Sector (1995)

Type of Air Conditioning System	Annual Unit Sales[2]	% Water Cooled (Installed Base)	Average Lifetime[1]	Installed Base[3]	Cooling Water Pump Motor - Typical	
					Horsepower (hp)	Efficiency (%)
Centrifugal Chiller	10,087	90	23	81,000	20	90
Screw Chiller	2,500	70	20	14,000	15	90
Reciprocating Chiller	13,000	50	20	105,000	5	88
LiBr — Water Absorption Chiller	500	100	23	8,000	25	90

Sources: 1 DOE, 1998
2 USCB, 1995(b)
3 ADL Estimates based on annual unit sales, % water cooled and average unit lifetimes

Table 4-8: Potential Energy Savings With Incrementally Higher-Efficiency Cooling Water Pump Drive Motors

Type of System	Typical Annual Operating Hours	Current Energy Consumption 10^9 kWh[4]	Efficiency (%)		Savings		Payback period (yrs)
			Current	Possible[1]	Site 10^9 kWh	Primary 10^{12} Btu	
Centrifugal Chiller[2]	1500	1.4	90	95	0.1	1.1	0.6
Screw Chiller[3]	1500	0.1	90	94	0.01	0.1	2.2
Reciprocating Chiller[3]	1500	0.7	88	93	0.04	0.4	1.7
LiBr Water Absorption Chiller[2]	1500	0.2	90	95	0.01	0.1	0.6
TOTAL		2.4	—	—	0.16	1.7	

Assumptions: Energy savings are calculated based on efficiencies shown, reflecting actual savings seen when replacing installed base with new motor. Payback is calculated based on costs and efficiencies from Table 2-1.

Sources: Tables 2-1 and 4-7

1 Maximum practical efficiency at median motor power, per Figure 2-3

2 Based on 25 hp motor costs and efficiencies

3 Based on 10 hp motor

*4 ADL estimate based on the calculation: Installed base * annual operating hours * [(assumed hp / efficiency) * 0.746], and a factor of 0.56 for condenser pumps.*

Within the loop, head losses consist of:

- Pressure loss through piping (wall friction, elbows, other fittings, and valves)
- Pressure loss through condenser tubing
- Pressure loss in cooling tower water piping and distribution nozzles
- Gravity head loss through cooling tower (height difference between the distribution nozzles and the sump)

The first three of these losses, which are flow friction losses following the familiar flow-rate-cubed vs. power characteristic, are 80 to 90 percent of the total head loss. The balance of the head loss is consumed by the gravity head loss in the cooling tower. At part load, with heat rejection well below design levels, a variable-speed drive on the pump motor could be used to reduce the flow rate. This would reduce power significantly due to the small fixed gravity head loss and the speed/flow-cubed power law. However, a reduction of the cooling water flow rate will result in a small increase in the condensing temperature, offsetting some of the pump power savings. An analysis of this trade-off is beyond the scope of this study. An upper bound on the potential energy savings and cost-effectiveness is established assuming that no additional compressor power results from reducing the cooling water flow rate at part load.

Power savings of 40 percent could be realized in a constant flow system, not including the fixed gravity head loss through the cooling tower, with potential total site energy savings of 1 billion kWh. Again, more detailed analysis of the impact on condensing temperature and compressor power consumption are needed to evaluate whether this is a viable approach for saving energy.

4.2.2.4 Heat Rejection to Ambient Air

The ultimate heat sink for nearly all commercial air-conditioning equipment, whether air or water-cooled, is ambient air. The cooling water in water-cooled systems usually passes through a cooling tower, which rejects heat to air as latent heat. Both air-cooled condensers and cooling towers require forced airflow over and through the heat or heat/mass transfer surface. Table 4-9 summarizes the numbers and sizes of motors typically used for heat rejection from commercial air conditioning systems. Table 4-10 summarizes the potential for energy savings through upgrading the efficiency of these motors from current levels to the best possible level.

Table 4-9: Motors in Commercial-Sector Air Conditioning Heat Rejection (1995)

Type of System	Annual Unit Sales[2]	Average Lifetime[1]	Installed Base[5]	Fan/Blower Motor	
				Horsepower	Efficiency
Room Air Conditioner[9]	829,860	11	9,128,460	1/10 – 1/3	50 – 70
PTAC[3,9]	212,418	15	3,186,270	1/10 – 1/4	50 – 70
Small Unitary[4]	589,100	15	6,193,029	1/4 – 1/2	50 – 70
Medium Unitary[4]	169,118	15	1,780,161	3/4 – 2	70 – 80
Large Unitary[4]	16,040	15	167,113	2 - 10	80 – 90
Air Cooled Screw Chillers	1,375[2,6]	20	6,000[5,7]	1 – 10	80 - 90
Air Cooled Reciprocating Chillers	13,000[2,8]	20	105,000[5,8]	2 - 10	80 – 90
Cooling Tower	8,948	20	178,960	5 - 25	80 – 90

Sources:
1 DOE, 1998
2 USCB, 1995(b)
3 Includes Packaged Terminal Heat Pumps
4 Single Packaged A/C and Year-round Packaged A/C
5 ADL Estimates based on annual unit sales and average unit lifetimes
6 ADL Estimates of new air cooled production @ 55 percent
7 ADL Estimates of current installed base @ 30 percent
8 ADL Estimates of current installed base and new production @ 50 percent
9 One double ended motor drives both the indoor air blower and the condenser fan. Energy savings already counted with interior air handling.

Table 4-10: Potential Energy Savings With Incrementally Higher-Efficiency Fan or Blower Drive Motors for Heat Rejection to Ambient Air—Commercial Buildings

Type of System	Typical Annual Operating Hours	Current Energy Consumption 10^9 kWh[7]	Efficiency (%)		Savings		Payback period (yrs)
			Current	Possible	Site 10^9 kWh	Primary 10^{12} Btu	
Room Air Conditioner[1]	—	—	—	—	—	—	—
PTAC[1]	—	—	—	—	—	—	—
Small Unitary[2]	1000	3.8	60	80	0.6	6.6	0.0
Medium Unitary[3]	1200	2.0	80	88	0.13	1.4	1.8
Large Unitary[4]	1500	1.1	85	90	0.05	0.6	1.7
Air Cooled Screw Chiller[5]	14,130	0.1	85	92	0.01	0.1	0.1
Air Cooled Reciprocating Chiller[5]	14,130	0.7	85	92	0.1	1.1	0.1
Cooling Tower[6]	2000	0.4	85	92	0.1	1.1	0.9
Total	—	8.1	—	—	1.0	10.9	—

Assumptions: Energy savings are calculated based on efficiencies shown, reflecting actual savings seen when replacing installed base with new motor. Payback is calculated based on costs and efficiencies from Table 2-1.

Sources: ADL Estimates, ADL 1998(a), Tables 2-1, 2-3 and 4-9

1 One double ended motor drives both indoor air blower and the condenser fan; energy already counted with interior air handling
2 Based on 1/2 hp induction motor. [Grainger] indicates no cost differential for high-efficiency motor
3 Based on 1 hp motor
4 Based on 5 hp motor
5 ADL estimate based on 2 hp motor; Weighted average [0.17 * (100 percent of Average # Fans) + 0.39 * (75 percent of Average # Fans) + 0.33 * (50 percent of Average # Fans) + 0.11 * (25 percent of Average # Fans)]. Average # Fans is approximately 14 based on manufacturer averages. Average operating hours for unit of 1500 hours from Table 4-1.
6 Based on 10 hp motor
*7 Calculation: Installed base * annual operating hours * [(assumed hp / efficiency) * 0.746]*

Reducing the fan speed of the condenser fan, the cooling tower fan and the blower fan, at part load, will lower the power consumption. However, reducing the fan speed and cooling airflow will result in an increase in the condensing temperature and compressor power, partially offsetting the power savings. The application of variable-speed drives to heat rejection fan and blower motors should be considered in the context of a system level evaluation of thermal distribution energy use.

4.2.3 Commercial Refrigeration

Commercial refrigeration equipment includes:

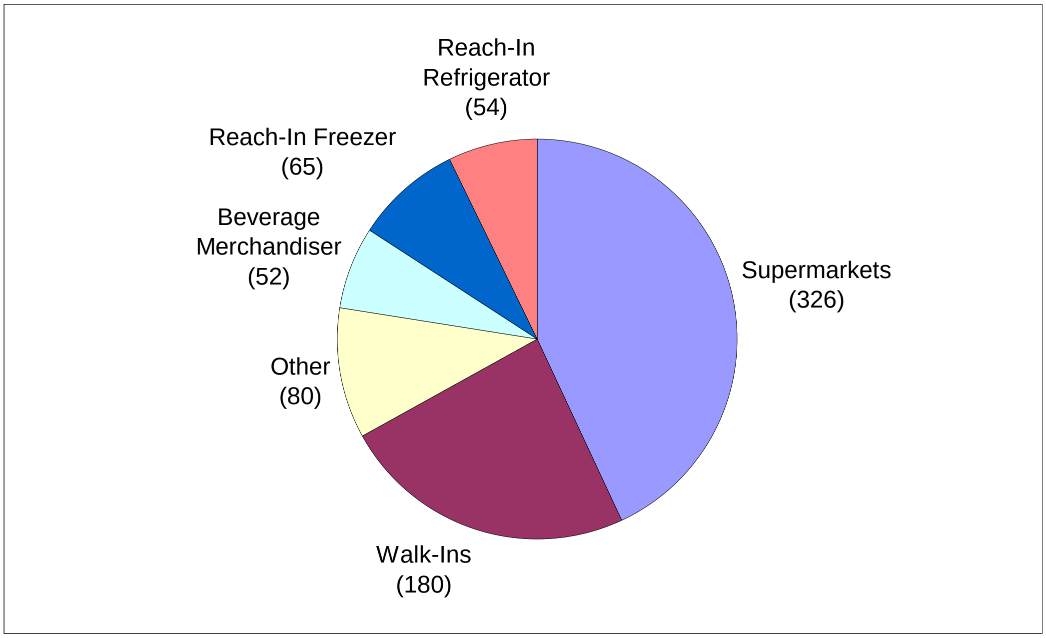
- Supermarket refrigerated display cases and walk-in refrigerators utilizing remote compressors and condensing equipment
- Self-contained systems (such as upright and horizontal merchandisers, beverage merchandisers, deli cases, reach-in and roll-in refrigerator/freezers, and under-counter refrigerator/freezers)
- Walk-in coolers and freezers
- Refrigerated vending machines
- Ice machines

Primary energy usage in the commercial refrigeration sector is approximately 993 trillion Btus. The contribution of different commercial refrigeration equipment types to this total is shown in Figure 4-8. Compressor and fan motor electricity consumption representing 760 trillion Btus (>76 percent of total energy) are summarized in Table 4-11 for the most common refrigeration applications. Typical performance data is included as a baseline for technical improvement.

The analyses below indicate that there are large opportunities for savings in the commercial refrigeration sector. This savings potential is associated with high-efficiency fan motors and high-efficiency compressors, technologies which, in refrigeration systems, have typical paybacks of less than two years when installed in new equipment. High-efficiency fan motors can also be implemented on a retrofit basis. Table 4-12 summarizes the energy savings possible in commercial refrigeration equipment. Payback economics are found in the tables describing individual technologies in the subsections below.

The savings potential for commercial refrigeration is more significant than for residential refrigeration because: (1) there has been no counterpart to NAECA in this sector to stimulate efficiency increases, and (2) the duty cycles typical for commercial fan and compressor motors are generally longer.

Figure 4-8: Primary Energy Usage in Commercial Refrigeration (total 993 trillion BTUs)



Source: ADL,1996

Table 4-11: Commercial Refrigeration Compressor and Fan Motor Energy Consumption

Equipment Type	Application	Number of Systems (x 1,000)	Typical Performance Data				Compressor Primary Energy Consumption 10^{12} Btu[1]	Fan Primary Energy Consumption 10^{12} Btu[1]
			Compressor hp	Compressor Motor Efficiency	Fan Motor Output	Fan Motor Efficiency		
Self-Contained	Reach-In Refrigerators	1,300[2]	1/3 -1/2	.7	6W - 1/15 hp	0.43 - 0.56	32	12
	Reach-In Freezers	800[2]	1/2-1	.7	6W - 1/15 hp	0.43 - 0.56	44	8
	Beverage Merchandisers	800[2]	1/3-3/4	.7	6W - 1/15 hp	0.17	22	15
	Roll-In Refrigerators & Freezers	250	1/3-1	.7	6W - 1/15 hp	0.43 - 0.58	8	3
	Other Refrigerators & Freezers (include non-beverage) merchandisers)	900	1/5-1/2	.7	6W - 1/15 hp	0.15 - 0.17	24	9
Vending Machines	Refrigerated Vending Machines	4,100[2]	1/3	.7	6W	0.15	59	20
Ice Makers	Ice Machine	1,200[2]		.42-.45	25W	.15 - .25	93	8
Centralized Systems	Walk-Ins: C-Store and Foodservice	880[2]	1/5-1/2	.7-.8	1/15 hp - 1/4 hp	0.25	99	57
	Small Grocery	20	5-50	0.7-0.8	6W - 1 hp	0.15 - 0.25	14	2
Rack Mounted	Supermarket	30	100-200[3]	0.88	6W - 1 hp	0.15 - 0.58	170	60
						Totals	**566**	**194**
						Grand Total		**760**

[1] Based on a heat rate of 11,005 Btu/kWh
[2] DOE, 1996
[3] 3 to 15 HP per compressor

Table 4-12: Commercial Refrigeration Compressor and Fan Motor Energy Savings

Equipment Type	Application	Number of Systems (x 1,000) [1]	Typical Performance Data: Compressor Primary Energy 10^{12} Btu [2]	Fan Primary Energy 10^{12} Btu [2]	Compressor % Savings [3]	Fan % Savings [3]	Compressor Primary Savings 10^{12} Btu [4]	Fan Primary Savings 10^{12} Btu [4]
Self-Contained	Reach-In Refrigerators	1,300	32	12	27%	47%	8.7	5.6
	Reach-In Freezers	800	44	8	28%	40%	12.5	3.3
	Beverage Merchandisers	800	22	15	32%	112% [5]	7.1	17.2
	Roll-In Refrigerators and Freezers	250	8	3	28%	40%	2.2	1.2
	Other Refrigerators and Freezers (include non-beverage merchandisers)	900	24	9	28%	77%	6.7	6.9
Vending Machines	Refrigerated Vending Machines	4,100	59	20	32%	110% [5]	18.6	22.2
Ice Makers	Ice Machine	1,200	93	8	6%	67%	5.8	6.3
Centralized Systems	Walk-ins: C-Store and Foodservice Refrigerators and Freezers	880 [6]	99	57	15%	52%	14.8	29.8
	Small Grocery	20	14	2	5%	77%	0.7	1.5
Rack-Mounted	Supermarket	30	170	60	5%	25%	8.5	15.0
		Totals	**566**	**194**		**Totals**	**85.6**	**109**

1 Based on ADL, 1996
2 Based on ADL, 1996, with conversion to primary energy at a heat rate of 11,005 Btu/kWh, compressor/fan percent of annual energy taken from prototypical unit
3 Based on compressor/fan savings divided by compressor/fan primary energy
4 Based on Tables 4-13 to 4-21 system energy reduction % for best available compressor or fan technologies, multiplied by energy consumption for total inventory of equipment type from Figure 4-8 converted at 11,005 Btu/kWh
5 Use of high-efficiency evaporator fans reduces compressor consumption; when compressor savings are accounted in this column, more than 100 percent of original fan use can be saved
6 Savings based on 590,000 walk-in refrigerators and 290,000 walk-in freezers
7 Note that compressor and fan savings are not directly additive because changes in compressor efficiency will change evaporator fan measure savings

4.2.3.1 Central Systems

There are approximately 30,000 supermarkets in the United States. Supermarkets represent about 7 percent of the country's commercial-sector electricity usage. About half of this usage is associated with supermarket refrigeration systems. Supermarkets range in size from less than 10,000 ft^2 to greater than 70,000 ft^2 total selling area. The average size is 26,715 ft^2.

A supermarket with a 45,000-ft^2 sales area and 24-hour operation is chosen as the baseline for the savings calculations for improved motor efficiency. The total annual electricity consumption for the model supermarket is 1.6 million kWh.

Supermarket refrigeration is divided into two distinct segments with different technologies that are governed by different issues. The more visible part of these systems is the display cases that hold food for the self-service shopping style of supermarkets. The display cases have their own electric loads, and they must be cooled by the store's refrigeration system.

The heart of supermarket refrigeration systems is represented by the compressor racks, which consist of a number of parallel-connected compressors located in a separate machine room. Each rack may have from three to five compressors serving a series of loads with nearly identical evaporator temperatures. A typical store will have 10 to 20 compressors in the 3-hp to 15-hp size range. Most compressor racks are "uneven parallel," meaning that the capacities of compressors in a rack are not equal. This improves the ability of the system to handle part-load conditions efficiently.

Because of the high duty cycle and tight operating margins, store operators are unwilling to invest in efficient equipment. The semi-hermetic refrigerant compressors are among the most efficient compressors in use. The typical efficiency of the 5 and 10 hp motors commonly used is 88 to 90 percent, with efficiencies a few percentage points higher being possible.

The principal opportunity for motor related energy savings in supermarket refrigeration resides in the use of more efficient evaporator fan motors. Most evaporator and condenser fan motors are inexpensive and inefficient single-phase shaded pole motors. The efficiency of permanent split capacitor (PSC) or ECPM motors is significantly better. Additionally, since evaporator fans contribute to refrigeration load, use of a high-efficiency, evaporator fan motor results in increased savings through the reduction in compressor load. Table 4-13 describes the economics of improved motor designs. The cost premiums and annual consumption reductions are based on the typical supermarket evaporator fan inventory shown in Table 4-14.

Table 4-13: Economic Analysis: Supermarkets

Motor Type	Reduction kWh/yr	Reduction kW	Cost Premium	Payback Period
PSC Evap Fan Motors	102,700	11.8	$7,600	0.9
ECPM Evap Fan Motors	131,200	14.9	$12,600	1.2

Assumptions: $0.08 per kWh electric rate; wattage and cost from Table 4-14, 100 percent fan duty cycle, 100 percent markup for end user from OEM motor costs; overall refrigeration COP of 1.9, which affects energy use through reduced compressor loading

Table 4-14: Evaporator Fan Motor Sizes and OEM Costs in a Typical Supermarket

Motor Output (W)	Total Number	Shaded Pole		PSC		ECPM	
		Total Cost	Total Power (W)	Total Cost	Total Power (W)	Total Cost	Total Power (W)
6	85	$595	3,400	$2,125	1,275	$2,975	720
9	100	$1,000	5,300	$2,800	2,100	$4,000	1,250
25	40	$1,000	4,400	$1,480	2,040	$1,920	1,320
Totals		$2,600	13,100	$6,410	5,420	$8,900	3,290

Source: ADL, 1996, Table 2-3

4.2.3.2 Beverage Merchandisers and Reach-In Equipment

This section describes the energy saving motor technologies and the energy savings potential that are applicable to beverage merchandisers. The technical and economic discussions are generalized to the entire class of unitary refrigeration equipment of which includes beverage merchandisers. Table 4-15 summarizes the energy reduction options.

The typical beverage merchandiser uses two 9W output shaded pole evaporator fan motors that use 53W of input power each. Replacement with PSC motors would save 64W in fan power, while ECPMs would save 81W for the system. Reduction in refrigeration load would increase energy savings by about an additional 60 percent of the fan motor savings.

The condenser fan motor is typically a shaded pole motor with a 53W input and a 9W output. Replacement with a PSC motor would save 32W, while replacement with an ECPM would save 40.5W.

The prototypical beverage merchandiser has a standard efficiency hermetic reciprocating compressor with a resistor start, induction run (RSIR) motor. The efficiency of the motor is about 70 percent, with input power nominally 425W. Efficiency modifications to the compressor include the use of a high-efficiency motor (80 percent), reducing suction gas pressure losses, reducing the valve clearance gap, reducing the heating of suction gas within

Table 4-15: Economic Analysis: Beverage Merchandiser

Baseline Energy Use: 3923 kWh/year for 1-Door Unit

Notes	Technology Option	End-User Cost Premium	Energy Reduction (kWh/yr)	System Energy Reduction %	Simple Payback Period (yrs)
1	PSC Evap Fan Motor	$72	887	23	1.0
2	ECPM Evap Fan Motor	$120	1118	29	1.4
3	PSC Cond. Fan Motor	$36	140	4	3.2
4	ECPM Cond. Fan Motor	$60	175	5	4.4
5	High-Eff. Compressor	$16	335	9	.6
6	ECPM Compressor Motor	$100	251	6	5.0
7	Variable-Speed Compressor	$150	536	14	3.7

Notes: 1&2 High-Efficiency Evaporator Fan Motors: Replacement of two 9-Watt output shaded pole motors with two 9-Watt output PSC or ECPM motors. Additional compressor load savings based on the 1.72 COP.

3&4 High-Efficiency Condenser Fan Motors: Replacement of one 9-Watt output shaded pole motor with a 9-Watt output PSC or ECPM motor. 50 percent duty cycle.

5 High-Efficiency Compressor: Increase in motor efficiency to 80 percent. OEM cost of $8, end user markup of 100 percent.

6&7 ECPM Compressor Motor/Variable-Speed Compressor: Replacement of the existing 1/3 hp motor with an ECPM motor (efficiency increase from 70 percent to 82 percent). Cost premium of $100 for the ECPM motor cost, $50 standard motor cost, 100 percent end-user markup). Additional 20 percent reduction in compressor energy usage for variable-speed operation. Controls cost for variable-speed operation of $50.

the compressor shell, reducing pressure drop through the discharge valve, and reducing mechanical losses.

The OEM costs for 1/3 hp compressors are about $40. Currently available high-efficiency compressors reportedly have a 10 percent cost premium. An $8 OEM cost premium is used in the economic analysis.

Further improvements in compressor efficiency would result from the use of ECPM compressor motors. Currently such compressors are not available except in limited numbers for special orders. The use of ECPM motors would allow variable-speed operation of the compressors when used in conjunction with appropriate controls. Variable-speed operation would allow further reductions in energy usage. For the economic analyses of the self-contained equipment, it is assumed that reductions in compressor power of 15 to 20 percent are possible with variable-speed operation. This reduction range has been achieved in tests at Arthur D. Little using two-speed compressor operation in a residential refrigerator/freezer.

Tables similar to 4-15 are presented for Reach-In Freezers (Table 4-16), Reach-In Refrigerators (Table 4-17), Ice Machines (Table 4-18), Vending Machines (Table 4-19), Walk-In Coolers (Table 4-20) and Walk-In Freezers (Table 4-21). All tables present energy reduction percentages based on reduction of energy use for the complete equipment system (e.g., beverage merchandiser). Savings are calculated based on a $0.08/kWh electric rate [DOE, 1998]. Cost and efficiency data are taken from, or consistent with, [ADL, 1996].

Table 4-16: Economic Analysis: Reach-In Freezers

Baseline Energy Use: 5198 kWh/year for Single-Door Unit

Notes	Technology Option	End-User Cost Premium	Energy Reduction (kWh/yr)	System Energy Reduction %	Simple Payback Period (yrs)
1	ECPM Evap Fan Motor	$24	118	2	2.5
2	ECPM Cond. Fan Motor	$24	138	3	2.2
3	High-Eff. Compressor	$24	831	16	0.4
4	ECPM Compressor Motor	$110	814	16	1.8
5	Variable-Speed Compressor	$160	986	19	2.1

Notes:
1 ECPM Evaporator Fan Motor: Replacement of one 9-Watt output PSC motor with one 9-Watt output ECPM motor. Additional compressor load savings based on a 1.25 COP.
2 ECPM Condenser Fan Motor: Replacement of one 1/20 hp PSC motor with a 1/20 hp ECPM motor. 75 percent duty cycle.
3 High-Efficiency Compressor: Increase in motor efficiency to 80 percent. OEM cost of $12, end user markup of 100 percent.
4&5 ECPM Compressor Motor/Variable-Speed Compressor: Replacement of the existing 1/2 hp motor with an ECPM motor (efficiency increase from 70 percent to 83 percent). Cost premium of $110 for the ECPM motor ($110 ECPM motor cost, $55 standard motor cost, 100 percent end-user mark-up). Additional 15 percent reduction in compressor energy usage for variable-speed operation. Controls cost for variable-speed operation of $50.

Table 4-17: Economic Analysis: Reach-In Refrigerators

Baseline Energy Use: 4321 kWh/year for Two-Door Unit

Notes	Technology Option	End-User Cost Premium	Energy Reduction (kWh/yr)	System Energy Reduction %	Simple Payback Period (yrs)
1	ECPM Evap Fan Motor	$48	300	7	2.0
2	ECPM Cond. Fan Motor	$22	142	3	2.0
3	High-Efficiency Compressor	$16	501	12	0.4
4	ECPM Compressor Motor	$100	367	8	3.5
5	Variable-Speed Compressor	$150	688	16	2.8

Notes: 1 ECPM Evaporator Fan Motor: Replacement of two 9-Watt output PSC motors with two 9-Watt output ECPM motors. Additional compressor load savings based on a 2.04 COP and an OEM motor cost of $28.

2 ECPM Condenser Fan Motor: Replacement of one 1/15 hp PSC motor with a 1/15 hp ECPM motor. 65 percent duty cycle.

3 High-Efficiency Compressor: Increase in motor efficiency to 80 percent. OEM cost of $12, end user markup of 100 percent.

4&5 ECPM Compressor Motor/Variable-Speed Compressor: Replacement of the existing 1/3 hp motor with an ECPM motor (efficiency increase from 70 percent to 82 percent). Cost premium of $110 for the ECPM motor ($100 ECPM motor cost, $50 standard motor cost, 100 percent end-user mark-up). Additional 15 percent reduction in compressor energy usage for variable-speed operation. Controls cost for variable-speed operation of $50.

4.2.3.3 Ice Machines

This section describes the energy-saving technologies that are applicable to ice machines; in particular to the 500-lb/day machine used for the baseline energy consumption.

The typical compressor used in ice machines in the 500-lb/day size range is a capacitor start-induction run reciprocating compressor with efficiencies in the 42 to 45 percent range. Capacitor start-capacitor run compressors are available with efficiencies 5 to 10 percent above the capacitor start induction run compressors. The higher-efficiency compressors cost $20 to $30 more than the standard-efficiency designs.

The prototypical condenser fan motor is a 110W shaded-pole motor. Comparable PSC motors are available that consume about 51W, resulting in a saving of 59W.

Table 4-18: Economic Analysis: Ice Machines

Baseline Energy Use: 5000 kWh/year

Notes	Technology Option	End-User Cost Premium	Energy Reduction (kWh/yr)	System Energy Reduction (%)	Simple Payback Period (yrs)
1	High-Efficiency Compressor	$40	280	6%	1.8
2	PSC Condenser Fan Motor	$24	233	5%	1.3
3	ECPM Condenser Fan Motor	$46	304	6%	1.9

Notes: 1 High-Efficiency Compressor: Assumes replacement of 3/4 hp CSIR compressor with CSCR compressor of about 6 percent greater efficiency

2&3 PSC & ECPM Condenser Fan Motor: Replacement of one 25W output shaded pole motor consuming 110W with a 51W consumption PSC motor, or with an ECPM motor consuming 33W. 45 percent duty cycle.

4.2.3.4 Refrigerated Vending Machines

Refrigerated vending machines are upright, refrigerated cases whose purpose is to hold cold beverages and/or food products and vend them in exchange for currency. The entire refrigeration system is built into the machine and heat is rejected from the refrigeration cycle to the surrounding air.

There is an estimated installed base of about 4,100,00 refrigerated vending machines [ADL, 1996]. The canned beverage vending machine was chosen for analysis in this report since it is the most common unit.

The refrigeration system components consist of a 1/3-hp hermetic compressor, one evaporator fan, and one condenser fan. All fans are equipped with shaded-pole motors.

Table 4-19: Economic Analysis: Refrigerated Vending Machines

Baseline Energy Use: 3000 kWh/year

Notes	Technology Option	End-User Cost Premium	Energy Reduction (kWh/yr)	System Energy Reduction %	Simple Payback Period (yrs)
1	PSC Evap Fan Motor	$36	305	10	1.5
2	ECPM Evap Fan Motor	$56	395	13	1.8
3	PSC Cond. Fan Motor	$36	77	3	5.8
4	ECPM Cond. Fan Motor	$56	97	3	7.2
5	High-Efficiency Compressor	$16	260	9	0.8
6	ECPM Compressor Motor	$100	191	6	6.7
7	Variable-Speed Compressor	$150	413	14	4.6

Notes: 1&2 High-Efficiency Evaporator Fan Motors: Replacement of one 6-Watt output shaded pole motor with one 6W output PSC or ECPM motor. Additional compressor load savings based on a 1.72 COP.

3&4 High-Efficiency Condenser Fan Motors: Replacement of one 6W output shaded pole motor with a 6W output PSC or ECPM motor. 35 percent duty cycle.

5 High-Efficiency Compressor: Increase in motor efficiency to 80 percent. OEM cost of $8, end user markup of 100 percent. 20 percent reduction in compressor power input, resulting in COP increase from 1.72 to 2.15.

6&7 ECPM Compressor Motor/Variable-Speed Compressor: Replacement of the existing 1/3 hp motor with an ECPM motor (efficiency increase from 70 percent to 82 percent). Cost premium of $100 for the ECPM motor ($100 ECPM motor cost, $50 standard motor cost, 100 percent end-user markup). Additional 20 percent reduction in compressor energy usage for variable-speed operation. Controls cost for variable-speed operation of $50.

4.2.3.5 Walk-In Coolers and Freezers

Walk-Ins typically use split systems with condenser units located on the roof or outside on a concrete pad. Compressors are usually of the welded hermetic and semi-hermetic type. The typical horsepower range of the compressor motors is from 1 to 5. The fan motors of walk-in evaporators are typically of the shaded-pole-type. Smaller condenser fan motors are also shaded pole, the larger motors typically being PSC.

Table 4-20: Economic Analysis: Walk-In Coolers

Baseline Energy Use: 42,306 kWh/year

Notes	Technology Option	End-User Cost Premium	Energy Reduction (kWh/yr)	System Energy Reduction %	Simple Payback Period (yrs)
1	PSC Evap Fan Motors	$160	3,228	8	0.6
2	ECPM Evap Fan Motors	$352	5,445	13	0.8
3	ECPM Cond Fan Motor	$60	925	2	0.8
4	High-Efficiency Compressor	$40	3,279	8	0.2

Notes: 1 PSC Evaporator Fan Motors: Replacement of eight 1/20hp output shaded pole motors with eight 1/20 hp output PSC motors. Additional compressor load savings based on 1.91 COP.

2 ECPM Evaporator Fan Motors: Replacement of eight 1/20hp output shaded pole motors with eight 1/20hp-output ECPM motors. Additional compressor load savings based on the 1.91 COP.

3 ECPM Condenser Fan Motor: Replacement of two-1/2 hp PSC motors with two 1/2-hp ECPM motors. 66 percent duty cycle.

4 High-Efficiency Compressor: Increase in COP from 1.91 to 2.24, resulting in a 15 percent reduction in compressor power input. OEM cost of $20, end user markup of 100 percent.

Table 4-21: Economic Analysis: Walk-In Freezers

Baseline Energy Use: 15,555 kWh/year

Notes	Technology Option	End-User Cost Premium	Energy Reduction (kWh/yr)	System Energy Reduction %	Simple Payback Period (yrs)
1	PSC Evap Fan Motor	$60	1,281	8	0.6
2	PSC Cond. Fan Motor	$22	779	5	0.4
3	ECPM Evap Fan Motors	$100	1,682	11	0.8
4	ECPM Cond Fan Motor	$48	1,067	7	0.6
5	High-Eff. Compressor	$50	1,330	9	0.5

Notes: 1 PSC Evaporator Fan Motors: Replacement of two 1/40 hp output shaded pole motors with two 1/40 hp output PSC motors. Additional compressor load savings based on a COP of 1.91.

2 PSC Condenser Fan Motor: Replacement of one 1/6 hp CSIR (329W input) motor with a 1/6 hp PSC motor. 70 percent duty cycle.

3 ECPM Evaporator Fan Motors: Replacement of two 1/40-hp output shaded pole motors with two 1/40-hp output ECPM motors. Additional compressor load savings based on a COP of 1.91.

4 ECPM Condenser Fan Motor: Replacement of one 1/6 hp CSIR (329W input) motor with a 1/6 hp ECPM motor. 70 percent duty cycle.

5 High-Efficiency Compressor: Increase in COP from 1.32 to 1.55, resulting in a 15 percent reduction in compressor power input from 1445W to 1228W. OEM cost of $25, end-user markup of 100 percent. 70 percent duty cycle.

4.2.4 Miscellaneous Commercial-Sector Motor Applications

About 93 percent of commercial-sector motor energy is consumed in the major applications discussed above. A number of the miscellaneous motor applications in the commercial sector are analogous to the residential sector in the sense that a diverse range is encompassed by applications that are economically important but low in one or more of the following: duty cycle, power consumption, or numbers in use. Examples include:

- Office equipment (personal computers, printers, photocopiers, etc.) cooling fans
- Photocopier and printer drive motors
- Commercial laundry equipment
- Vacuum cleaners, floor polishers, carpet cleaners, etc.
- Commercial kitchen equipment (food mixers, meat slicers, etc.)
- Air compressors
- Power tools

In general, these motors perform many useful functions, which are out of proportion to their energy consumption. While the motor efficiencies are often low, the total energy consumed by these motors is insignificant, due to their small numbers, lower power rating, and/or low duty cycle.

5 Market Barriers to Increased Use of High-Efficiency Motors

To be able to formulate programs that increase the efficiency of motor systems in the commercial and residential sectors, it is necessary to obtain a clear understanding of the major stakeholders in the various categories of motor applications. Successful programs must be tailored to the essential decision-makers and be consistent with their particular business practices. Given the large variations among the investigated market segments regarding such fundamental characteristics as market needs, market drivers, purchasing criteria and decision makers, it is imperative that the selected policies be responsive to the uniqueness of each group. The following discussion of market barriers to improved motor efficiency identifies the essential players and major issues.

The motor and variable-speed drive markets have numerous stakeholders with many different and sometimes conflicting interests. Interested parties include motor end-users, motor and drive manufacturers, original equipment manufacturers (OEM), equipment distributors, trade associations, electric utilities, certification organizations, research centers, government agencies, engineering firms and construction companies. The exact role and the relative importance of each stakeholder can vary significantly across markets and even within markets. Our discussion of market barriers to improved motor efficiency will primarily cover the two areas of motor market and stakeholder.

5.1 Residential

In residential appliances, the primary barrier to the use of incrementally more expensive, higher-efficiency components is the combined effect of typical consumer appliance purchase decision priorities and the stringently competitive pricing faced by manufacturers, distributors, and retailers. Efficiency is only one of the many features sought by consumers, and all evidence indicates that efficiency is typically a low priority, well behind first cost and utility/styling features. The competitive pricing environment forces manufacturers, distributors, and retailers alike to accept comparatively low prices and margins, and to attempt to cut costs at all levels to maintain margins. For the manufacturer, this means specifying lower cost components. For the retailer, it means expensive showroom floor space, display samples, and the selection of inventory, which offers a variety of price levels, and features in which consumers have a demonstrated interest.

A second barrier is that individuals other than those responsible for paying the electric bill select a significant number of residential appliances. Most often, this individual is a builder, whose primary interest is in providing the required functions of heating, air conditioning, and refrigeration at the lowest initial cost, with little regard to the continuing operating cost.

As discussed in Section 3.1, NAECA standards have significantly raised the minimum efficiency levels for the applications that together use more than 85 percent of residential sector motor energy. For these applications—refrigerators, window air conditioners, central air conditioners, heat pumps, dishwashers and laundry appliances—current standards are sufficiently stringent (with more stringent standards levels under consideration in the rulemaking process) to have shifted manufacturers' design trade-offs. Furnace blowers are the one motor-driven application that stand out as significant in residential energy consumption and not yet covered by NAECA standards. Expectations are that this use will eventually be covered by standards, but differences regarding the approach that should be taken to do this are not yet resolved.

Variable-speed motors have not proven very cost-effective as yet, but there is evidence that the new NAECA standard levels for these appliances will lead to significantly increased use of variable-speed drives. The increased volume could result in gradually falling costs. The use of variable speed switched reluctance motors in Maytag washers are an example of this increased use.

5.2 Commercial Refrigeration

End Users

The needs, attitudes, decision criteria, and decision making process for the refrigeration equipment end-user vary across product lines. Generally, it may be useful to distinguish between end-users that pay their own energy costs and those who do not. For example, most vending machines are owned by bottling companies who do not pay utility bills in the buildings where the units are located. This effectively eliminates any incentive for the bottling companies to select the higher priced, but more efficient machines.

By contrast, supermarkets are responsible for their own energy bills, which are of the same order as the net margins realized in the highly competitive supermarket industry (1/2 to 1 percent of sales). This has led to an emphasis on the energy savings in the design and specification of refrigeration systems, particularly in supermarket chains that have access to the necessary capital and central engineering staffs. Even so, the emphasis on efficiency has been most pronounced in the central refrigeration systems—the compressor racks and condensers. Marketing staff, with merchandising considerations overshadowing efficiency has controlled selection of display cases.

Many refrigeration products are sold to non-chain convenience stores, smaller grocers, and restaurants. This market segment encounters many additional barriers. Some examples include a lack of awareness of the energy savings potential, payback expectations of three years or less, a strong risk aversion to new technologies, market fragmentation, higher business risk and less capital availability. Walk-In Refrigerator/Freezers and Reach-Ins are the most affected products.

Manufacturers

Supermarket refrigeration systems are very often custom designed for a particular store layout and equipment loads. Hence it is difficult to supply supermarket industry professionals with general performance criteria from which to evaluate their systems' energy usage. Without a baseline consumption or standardized system configuration that could be optimized through experience, designers are constantly re-engineering with varying degrees of success. Furthermore, stores are frequently re-modeled and display cases are added or deleted. This alters the system loads and configurations.

The production numbers for commercial refrigeration equipment is low in comparison to residential products such as refrigerator/freezers. The engineering and tooling costs associated with commercial equipment cannot be allocated to as may units. Since the market is competitive, this creates a disincentive to an improved product design.

5.3 Air Conditioning Compressors/Commercial HVAC

End-Users

Grouped metering and insufficient feedback to commercial tenants have been cited as major barriers to the more efficient use of energy. In many commercial buildings, electricity metering is grouped for several tenants and so individual tenants have no direct incentive to lower their own consumption. Commercial leases often pass down shared services on a square feet leased basis. Larger lease charges and fees thus mask the energy costs. Very often, the commercial tenant is part of a larger chain or corporate entity that pays the lease and utility bills. The tenant may never see the utility bills and will not receive any feedback on the energy consumption.

Many tenants of commercial space associate reduced energy consumption with reduced comfort. This is particularly true of measures designed to setback room temperature levels or reduce ventilation rates.

Finally, separation of equipment ownership from responsibility for utility bills is the major hurdle in commercial facilities. Although many commercial tenants may have their separate HVAC unit, it is owned and usually maintained by the building owner that makes little, if any, effort to improve energy efficiency since energy costs are passed down to the tenants. Similarly, decisions as to what HVAC equipment is installed is not made by the person responsible for the energy bills. Some criteria that are more important to the building developer include lower first cost and a familiarity with the equipment to be installed.

5.4 HVAC Thermal Distribution/Adjustable-Speed Drives

End-Users

While it is certain that in many applications, VSDs can significantly reduce fan and pump energy, an engineering analysis is normally required to estimate the cost-effectiveness of a particular application. Calculations of site-specific energy savings involve knowledge of present flow variations in the system and of the current methods used for control.

ASD projects require careful evaluations that can often lie outside a client's technical ability or the availability of time. Without a professional review, installations may not be well designed, the applications wrong, and the savings overstated.

Engineering Firms

One of the main issues facing the acceptance of VSDs in the design phase of the commercial building plan, is the lack of trained and experienced consulting engineers who have the required knowledge to design these systems. The potential for litigation seriously contributes to risk aversion and limits any new product acceptance.

Variable-speed drives require considerable technical experience on the part of the system designer to avoid potentially costly design problems. VSDs must be matched, correctly, to the host electrical distribution system. Power quality deterioration, motor stress, noise, and damaging vibration can result from ASD misapplication. Additionally, in some cases, VSDs may require the installation of new electrical protection devices or the purchase of new, more efficient motors.

Faced with competitive pressures, engineering design has drifted to "boilerplate" approaches that make maximum use of "packaged" equipment solutions. Systems engineering, the careful consideration of optimal flows and pressures is reluctantly, yet necessarily replaced by convenient rules-of-thumb. System optimization could end up as a lost art unless it becomes recognized and rewarded.

Contractors

VSDs represent a relatively new technology that is unfamiliar to many mechanical and electrical contractors. Their lack of product knowledge translates into lost opportunities in the retrofit market and leads to the adoption of a "risk premium" on new construction projects where the equipment is specified.

Distributors

The complexity in VSD applications essentially makes them specialty items that most electrical equipment distributors do not stock. The manufacturer's representative who often provides considerable benefit in assisting the engineer or contractor in the system design dominates the sales channel. The added service translates into higher product costs. In this situation, the distributor's role is limited to assuming the credit risk.

Utilities

The site-specific nature of ASD savings does not lend itself particularly well to generic rebates such as payments per HP. The trend in regulatory circles is increasingly towards verified kW and kWh savings. High DSM programmatic costs may result from the need to perform pre-implementation audits and post-implementation monitoring. ESCO type performance contracting seems well suited to the installation of VSDs but the transaction costs can be significant.

6 Bibliography

ACEEE 1991. Energy Efficient Motor Systems–A Handbook on Technology Programs, and Policy Opportunities. American Council for an Energy–Efficient Economy (ACEEE). 1991.

ACEEE 1995. Elliott, R.N.. Energy Efficiency in Electric Motor Systems. American Council for an Energy-Efficient Economy (ACEEE). April 1995.

ACEEE 1996. Friedman, N.R., et al.. Electric Motor System Market Transformation, American Council for an Energy-Efficient Economy (ACEEE). March 1996.

Americold, 1990 (January). Private communication.

Appliance 1998. "Statistical Review — 45th Annual Report of the U.S. Appliance Industry". Appliance Magazine. April 1998.

Appliance Magazine Web site, Appliance Magazine, April 1998, "http://www.appliance.com"

ADL 1990 (August). Impact of a CFC Ban on the Cost and Performance of Household Refrigerators, Centrifugal Chillers, and Commercial/Industrial Refrigeration Systems. Arthur D. Little, Inc. Technical Memorandum to U.S. DOE.

ADL 1993. Patel, R.. Characterization of Commercial Building Appliances. Arthur D. Little, Inc.. August 1993.

ADL 1996. Energy Savings Potential for Commercial Refrigeration Equipment. Arthur D. Little for U.S. Department of Energy, Office of Building Technologies. June 1996.

ADL 1998. Zogg, R.A. and Alberino, D.L., Electricity Consumption by Small End Uses in Residential Buildings. Arthur D. Little for U.S. Department of Energy, Office of Building Technologies, Contract No. DE-AC01-96CE23798. August 1998.

ADL 1998(a). Westphalen, D. and Koszalinski, S.A., Commercial Building Energy Use - Volume II: Thermal Distribution, Auxiliary Equipment, and Ventilation. Arthur D. Little for U.S. Department of Energy, Office of Building Technologies, Contract No. DE-AC01-96CE23798, Task Assignment #4. November 24, 1998.

AEO 1998. Annual Energy Outlook 1998. Energy Information Administration, Report No. DOE/EIA-0383 (98). December 1997.

Baldor, 1989 (November). Private communication.

Beard 1994. Comments of the Associate of Home Appliance Manufacturers Regarding Energy Efficiency Standards for Room Air Conditioners. Docket No. EE-RM-90-201. July 18, 1994.

Cann, P. 1989 (November 28 - December 1). “Integrated Heat Pumps,” Meeting Customer Needs with Heat Pumps. Atlanta, GA., Sponsored by EPRI.

CBECS 1989. Commercial Buildings Characteristics - 1989. DOE/EIA-0246(89). June 1991.

CBECS 1989. Commercial Buildings Energy Consumption and Expenditures—1989. DOE/EIA-0318(89). April 1992.

Copeland, 1990 (January). Private communication.

Dickey, 1994. Testimony before the US. Department of Energy, Office of Energy Efficiency and Renewable Energy, EE-431, Energy Conservation Program for Consumer Products, Docket No. EE-RM-90-201, 50 Federal Register, pg. 10464, March 4, 1994.

Dieckmann 1993. State-of-the-Art Survey of Motor Technology Applicable to Hermetic Compressors for Domestic Refrigerator/Freezers. J. Dieckmann and E. McMahon. U.S. EPA Report, EPA-430-R-93-009, Global Change Division, Office of Atmospheric Programs, Washington, DC. April 1993.

Dieckmann 1993. State-of-the-Art-Survey of Hermetic Compressor Technology Applicable to Domestic Refrigerator/Freezers. J. Dieckmann and W. Johnson. U.S. EPA Report EPA-430-R-93-010, Global Change Division, Office of Atmospheric Programs, Washington, DC. April 1993.

DOE 1996. National Market Transformation Strategies for Industrial Electric Motor Systems. U.S. Department of Energy, Office of Industrial Technologies. May 1996.

DOE 1998. U.S. Department of Energy, Office of Building Technology, State and Community Programs Core Databook. June 12, 1998.

DOE/OIT, 1998. United States Industrial Electric Motors Systems Market Opportunities Assessment. Xenergy, Inc.. August 22, 1998.

Electric Power Research Institute, 1987. ASD Directory. Second Edition. Palo Alto, California.

Emerson Electric, 1990 (January). Private communication.

EPA 1993. Multiple Pathways to Super-Efficient Refrigerators. United States Environmental Protection Agency. June 1993. EPA-430-R-93-008.

EPRI, 1992 (June). Electrical Motors - Markets, Trends and Applications. EPRI TR-100423.

Federal Register, 1989a (February 7), pp. 6077-8.

Federal Register, 1989b (November 17), pp. 47916-47938.

Federal Register, 1991 (May 14). Energy Conservation Program for Consumer Products: Final Rule Regarding Energy Conservation Standards for Three Types of Consumer Products. pp. 22267-8.

Fitzgerald, A.E., Kingsley, C. Jr., Urmans, S.D., Electric Machinery. McGraw-Hill, 1990.

GE Motors, 1990a (January 12), Telefax summarizing induction motor efficiencies.

GE Motors, 1990b (January). Private communication.

Grainger, 1998-99. W. W. Grainger General Catalog No. 389.

Greenberg, S., et al., 1988 (March). Technology Assessment: Adjustable-speed Motors and Motor Drives (Residential and Commercial Sectors). LBL-25080.

GRI, 1989, Hurley, J., Shukla, K., and Kohli, P., Commercial Appliance Energy Use Update-1989. GRI-92/0225.

LBL, 1996. Draft Report on Energy Conservation Potential for Small Electric Motors. Lawrence Berkeley National Laboratory for U.S. Department of Energy, Office of Codes and Standards. August 1996.

LBL, 1998. Sanchez, M.C., et al., Miscellaneous Electricity Use in the U.S. Residential Sector. Ernest Orlando, Lawrence Berkeley National Laboratory, Draft Report No. LBL-40295. January 1998.

Lloyd, J. D. 1982. Variable-Speed Compressor Motors Operated on Inverters. AHSRAE Transactions V88, pt 1.

Lorenz, A., Meutzner, K. 1975. On Application of Non-azeotropic Two-component Refrigerants in Domestic Refrigerators and Home Freezers. IIR.

Lovins, A. B., et al., 1989 Edition (April). The State of the Art: Drivepower, A Competitek Report published by the Rocky Mountain Institute. Snowmass, CO.

MotorMaster+ 3.0 Database. Washington State Energy Office. 1998.

RECS 1992. Housing Characteristics 1990. Residential Energy Consumption Survey, DOE/EIA-0314(90). May 1992.

RECS 1993. Household Energy Consumption and Expenditures 1990. Residential Energy Consumption Survey, DOE/EIA-0321(90). February 1993.

Slemon, G.R.. Electric Machines and Drives. Addison-Wesley. 1992.

Smith, A.O., 1990 (January). Private communication.

Sulfstede, L., 1989 (November 28 - December 1). Residential Variable Speed Technology - Meeting Customer Needs with Heat Pumps. Atlanta, GA, Sponsored by EPRI.

Sun, Tseng-Yoo, 1993. "The Variety of Air Handling Systems," Heating, Piping, and Air Conditioning, pp. 53 – 60. December, 1993.

Toshiba(a) International Corporation, Houston, Texas. Toshiba Instruction and Maintenance Manual - Tosvert - 130E Transistor Inverter. Bulletin No. IMVT130E230.

Toshiba(b) International Corporation, Houston, Texas, Toshiba Inverter Seminar (a 20-page brochure published by Toshiba).

USCB 1995(a). Major Household Appliances. U.S. Census Bureau, Report No. MA36F, 1995.

USCB 1995(b). Refrigeration and Heating Equipment. U.S. Census Bureau, Report No. MA35M, 1995.

ZBA 1993. Communication with William Bahnfleth, ZBA, Inc. Engineers/Architects. June 1993.

Filename:	DOE Motor Report 2-2-00.doc
Directory:	C:\Docs
Template:	C:\Program Files\Microsoft Office\Templates\Normal.dot
Title:	A Head
Subject:	
Author:	COMDISCO\ARTHUR D LITTLE INC
Keywords:	
Comments:	
Creation Date:	02/02/00 2:03 PM
Change Number:	4
Last Saved On:	02/02/00 2:37 PM
Last Saved By:	Stephen DiBenedetto
Total Editing Time:	11 Minutes
Last Printed On:	02/02/00 2:49 PM

As of Last Complete Printing

Number of Pages:	130
Number of Words:	35,922 (approx.)
Number of Characters:	204,760 (approx.)